Land Use and Cover or Precipitation?

Changes on Hydrological Response of the Upper Paraná River Basin

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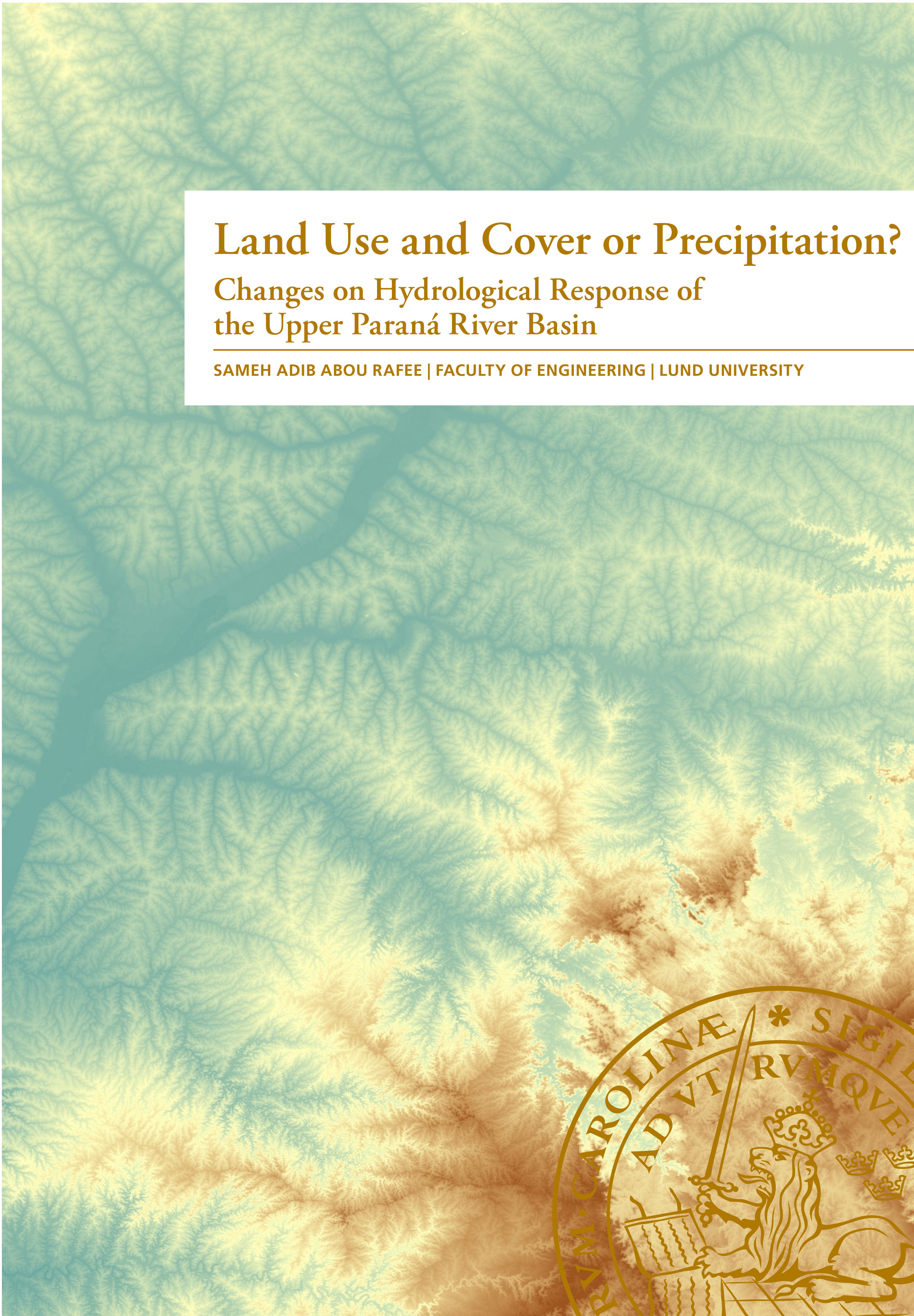

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SAMEH ADIB ABOU RAFEE | FACULTY OF ENGINEERING | LUND UNIVERSITY

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Sameh Adib Abou Rafee

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Abstract

The Upper Paraná River Basin (UPRB) has undergone extensive Land Use and Cover Changes (LUCC) in the latest decades, due to rapid population growth and economic development. Furthermore, variation in precipitation patterns was observed across the basin mainly after the 1970s Climate shift. Concurrently, the UPRB has presented significant changes in its hydrology. In this context, this thesis investigates the changes in precipitation and LUCC and their effects on the hydrological processes in the UPRB. The observed trends in the extreme precipitation events from 1977 to 2016 were evaluated using the Mann–Kendall test. Different numerical scenarios were simulated using the Soil and Water Assessment Tool (SWAT) model. The model was calibrated and validated with a satisfactory performance for the main rivers during the period 1984 – 2015 considering the Land Use and Cover (LUC) from 2015. The results revealed that the southern (northern) parts of the basin presented increasing (decreasing) trends in precipitation amounts. Besides, the southern regions of the UPRB presented an increase in the number of rainstorms > 50 mm day^{-1} and annual greatest 5-day total precipitation, while the northern part an increase in the number of consecutive dry days. The results also suggest that the basin is exposed to a longer rainy season. By comparing the LUC between 1985 and 2015, the numerical simulations showed that the natural vegetation suppression caused significant changes in basin hydrology. For instance, an increase (decrease) of surface runoff in the wet (dry) season at most UPRB subbasins, was observed. In addition, the simulations revealed a reduction in actual evapotranspiration and an increase in soil moisture in the annual and wet season. Consequently, the major rivers of the basin presented an increase (decrease) in their discharge in the wet (dry) period. This study also addressed the comparison between the LUC from a pristine period (around the year 1500), 1960 and 1985, and changes in precipitation before and after the 1970s Climate shift. In this case, the results showed that the 1970s Climate shift event has a higher effect on the changes in average annual discharge at the river mouth of the UPRB. This research improves the understanding of the effects of LUCC and changes in precipitation patterns on the hydrology across the UPRB. The results from this thesis will hopefully provide insights in improving sustainable management of water resources.

Key words: discharge, SWAT model, trend analysis, large-scale modelling

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To Abou Rafee family

Everything in life has the same importance until the moment you give value to each of it

Sameh Adib Abou Rafee

Contents

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وأخيراً ، اقدم شكري الخالص لوالدي الغالي أديب يوسف أبو رافع ووالدتي سلامية سيف الدين أبو رافع ، الكلمات تعجزعن التعبير عن امتناني وعرفاني لكم . أنا مدين لكم بكل ما وصلت إليه في حياتي ومسيرتي المهنية. كما أود أن أعرب عن خالص امتناني لإخواني علاء ويوسف وسامر أبو رافع.

عائلة ابو رافع انتم الافضل.

Popular summary

Land use and cover and precipitation changes are the most critical factors that affect the hydrological processes. The Upper Paraná River Basin, one of the largest and most socio-economically important river basins in South America has undergone extensive natural vegetation suppression during the latest decades. For example, cerrado (Brazilian savanna) had a reduction of about 173 000 km^2 between 1985 and 2015. Also, precipitation changes after the 1970s were witnessed over basin areas due to a global climatic event known as "climate shift". This work addressed the behavior and effects of these changes on hydrology within the basin.

During the last four decades, between 1977 and 2016, the Upper Parana River has experienced changes in precipitation. For example, the provided results showed that the northern part of the basin mostly presented decreasing in seasonal and annual precipitation totals following the increasing of the consecutive number of days without rain. On the other hand, in the southern areas of the basin, an increase in precipitation totals and rainstorms more pronounced during the summer was observed. Besides, the analyses suggest that most of the areas across the basin are exposed to a longer rainy season.

Furthermore, this study showed that the changes in land use and cover between 1985 and 2015 have a significant effect on basin hydrology. For example, it was observed an increase in discharge at the largest rivers of the basin during the wet season. This followed the decrease in evapotranspiration and both increase in surface runoff and soil moisture. The main reason for these changes was the natural deforestation that has been replaced by cropland or grassland areas.

In the last part of this work, the cause for the observed increase of about 26% in the annual discharge after the 1970s at the Lower Paraná River was assessed. For that, both effects on the discharge from land use and cover change since the pristine period (around the Year 1500) until 1985, and precipitation change due the 1970s climate shift were addressed together and separately. The results showed that both changes that happened within the basin have a significant impact on the annual discharge, but the precipitation change after the 1970s being the main driver.

This work suggests the importance of addressing large-scale land use and cover change and global climate shift impacts on hydrology. Hence, these changes should be regarded with much attention by the environmental managers worldwide.

Abstract

The Upper Paraná River Basin (UPRB) has undergone extensive Land Use and Cover Changes (LUCC) in the latest decades, due to rapid population growth and economic development. Furthermore, variation in precipitation patterns was observed across the basin mainly after the 1970s Climate shift. Concurrently, the UPRB has presented significant changes in its hydrology. In this context, this thesis investigates the changes in precipitation and LUCC and their effects on the hydrological processes in the UPRB. The observed trends in the extreme precipitation events from 1977 to 2016 were evaluated using the Mann–Kendall test. Different numerical scenarios were simulated using the Soil and Water Assessment Tool (SWAT) model. The model was calibrated and validated with a satisfactory performance for the main rivers during the period 1984 – 2015 considering the Land Use and Cover (LUC) from 2015. The results revealed that the southern (northern) parts of the basin presented increasing (decreasing) trends in precipitation amounts. Besides, the southern regions of the UPRB presented an increase in the number of rainstorms > 50 mm day^{-1} and annual greatest 5-day total precipitation, while the northern part an increase in the number of consecutive dry days. The results also suggest that the basin is exposed to a longer rainy season. By comparing the LUC between 1985 and 2015, the numerical simulations showed that the natural vegetation suppression caused significant changes in basin hydrology. For instance, an increase (decrease) of surface runoff in the wet (dry) season at most UPRB subbasins, was observed. In addition, the simulations revealed a reduction in actual evapotranspiration and an increase in soil moisture in the annual and wet season. Consequently, the major rivers of the basin presented an increase (decrease) in their discharge in the wet (dry) period. This study also addressed the comparison between the LUC from a pristine period (around the year 1500), 1960 and 1985, and changes in precipitation before and after the 1970s Climate shift. In this case, the results showed that the 1970s Climate shift event has a higher effect on the changes in average annual discharge at the river mouth of the UPRB. This research improves the understanding of the effects of LUCC and changes in precipitation patterns on the hydrology across the UPRB. The results from this thesis will hopefully provide insights in improving sustainable management of water resources.

Keywords: discharge, SWAT model, trend analysis, large-scale modelling.

Sammanfattning

Övre Paraná avrinningsområdet (UPRB) har genomgått omfattande markanvändnings- och täcknings-ändringar (LUCC) under de senaste decennierna på grund av snabb befolkningstillväxt och ekonomisk utveckling. Dessutom observerades variationer i nederbördsmönstren över avrinningsområdet främst efter 1970-talets climate-shift.. Samtidigt har UPRB presenterat betydande förändringar i sin hydrologi. Denna avhandling undersöker förändringarna i nederbörd och LUCC, och deras effekter på de hydrologiska processerna i UPRB. De observerade trenderna i de extrema nederbördshändelserna från 1977 till 2016 utvärderades med hjälp av Mann-Kendall-testet. Olika numeriska scenarier simulerades med hjälp av SWAT-modellen (Soil and Water Assessment Tool). Modellen kalibrerades och validerades för de viktigaste floderna under perioden 1984 - 2015 med tanke på markanvändningen och täckningen (LUC) från 2015. Resultaten visade att de södra (norra) delarna av avrinningsområdet presenterade ökande (minskande) trender i nederbördsmängder. Dessutom presenterade de södra regionerna i UPRB en ökning i antalet regnstormar> 50 mm dag-1 och i den årlig största 5-dagars total nederbörden, medan den norra delen en ökning i på varandra följande antal torra dagar. Resultaten visade också att bassängen presenterar en allt längre regnperiod. Genom att jämföra LUC mellan 1985 och 2015 visade de numeriska simuleringarna att det naturliga vegetationsundertrycket orsakade betydande förändringar i UPRBs hydrologin. Till exempel observerades en ökning (minskning) av ytavströmningen i den våta (torra) säsongen vid de flesta UPRB-underbassänger. Vidare visade simuleringarna en minskning av den faktiska evapotranspirationen och en ökning av markfuktigheten under den årliga våta säsongen. Följaktligen uppvisade de stora floderna i UPRB en ökning (minskning) av deras flöde under den våta (torra) perioden. Denna studie behandlade också jämförelsen mellan LUC från en orörd period (omkring år 1500), 1960 och 1985, och förändringar i nederbörd före och efter 1970-talets klimatförändring. I det här fallet visade resultaten att händelsen av klimatförändring på 1970-talet har en högre effekt på förändringarna i den genomsnittliga årliga flöde vid UPRB-flodmynningen. Denna forskning förbättrar förståelsen för effekterna av LUCC och förändringar i nederbördsmönster på hydrologin över UPRB. Resultaten från undersökningen kan förhoppningsvis användas för att förbättra hållbar förvaltning av vattenresurserna

Nyckelord: flöde, SWAT-modell, trend analys, storskalig modellering.

Resumo

A Bacia do Alto do Rio Paraná (BARP) passou por extensas Mudanças no Uso e Cobertura da Terra (MUCT) nas últimas décadas, devido ao rápido crescimento populacional e desenvolvimento econômico. Além disso, foi observada uma variação nos padrões de precipitação na bacia, principalmente após evento de alteração climática observado na década de 1970. Ao mesmo tempo, a BARP apresentou mudanças significativas em sua hidrologia. Nesse contexto, esta tese investigou as mudanças na precipitação e as MUCT, e seus efeitos nos processos hidrológicos na BARP. A tendência dos eventos extremos de precipitação entre 1977 e 2016 foram avaliados utilizando o teste de Mann-Kendall. Diferentes cenários numéricos foram simulados utilizando o modelo *Soil and Water Assessment Tool* (SWAT). O modelo foi calibrado e validado com desempenho satisfatório para os principais rios durante o período 1984 – 2015 considerando o Uso e Cobertura da Terra (UCT) de 2015. Os resultados revelaram que as partes sul (norte) da bacia apresentaram tendências crescentes (decrescentes) nas quantidades de precipitação. Além disso, as regiões sul da BARP apresentaram um aumento no número de tempestades > 50 mm dia^{-1} e na máxima precipitação anual em 5 dias consecutivos, enquanto a parte norte um aumento no número consecutivos de dias secos. Simultaneamente, os resultados mostraram que a maior parte da bacia apresenta uma estação chuvosa cada vez mais longa. Na comparação entre o UCT de 1985 e 2015, as simulações numéricas mostraram que a supressão natural da vegetação causou mudanças significativas na hidrologia da bacia. Por exemplo, um aumento (diminuição) foi observado no escoamento superficial durante a estação chuvosa (seca) na maioria das subbacias da BARP. Além disso, as simulações revelaram uma redução na evapotranspiração real e aumento na umidade do solo anual e na estação chuvosa. Consequentemente, os principais rios da bacia apresentaram um aumento (diminuição) na vazão no período chuvoso (seco). Este estudo também abordou a comparação entre o UCT de um período primitivo (por volta do ano 1500), 1960 e 1985, e as mudanças na precipitação antes e depois da alteração climática. Nesse caso, os resultados mostraram que a alteração climática de 1970 tem um maior efeito na vazão média anual no exutório da BARP. Esta pesquisa apresenta uma melhor compreensão dos efeitos das MUCT e mudanças nos padrões de precipitação sobre a hidrologia da BARP. Os resultados apresentados oferecem subsídios no sentido de melhorar a gestão sustentável dos recursos hídricos.

Palavras-chave: vazão, modelo SWAT, analise de tendência, modelagem de larga escala.

Resumen

La Cuenca del Alto Río Paraná (CARP) ha sufrido grandes Cambios en el Uso y Cobertura de la Tierra (CUCT) en las últimas décadas, debido al rápido crecimiento de la población y al desarrollo económico. Además, se observó una variación en los patrones de precipitación en la cuenca, principalmente después del evento de alteración climática observado en la década de 1970. Al mismo tiempo, la CARP mostró cambios significativos en su hidrología. Por lo expuesto, esta tesis investigó los cambios en la precipitación y en los CUCT, y sus efectos sobre los procesos hidrológicos en la CARP. La tendencia en los eventos de precipitación extrema fue evaluada durante el periodo 1977 – 2016 a través de la aplicación del test estadístico de Mann-Kendall. Diferentes escenarios numéricos fueron simulados con el modelo *Soil and Water Assessment Tool* (SWAT). El modelo fue calibrado y validado con un desempeño satisfactorio para los ríos principales de la cuenca durante el período 1984 – 2015 considerando el Uso y Cobertura de la Tierra (UCT) de 2015. Los resultados revelaron que partes del sur (norte) de la cuenca presentaron tendencias crecientes (decrecientes) en las cantidades de precipitación. Además, las regiones del sur de la CARP presentaron un aumento en el número de tormentas > 50 mm día^{-1} y en el máximo anual de la precipitación acumulada en cinco días consecutivos, mientras la parte norte aumentó el número de días secos consecutivos. Simultáneamente, los resultados mostraron que la cuenca presenta una temporada de lluvia cada vez más larga. Al comparar el UCT de 1985 y 2015, las simulaciones numéricas mostraron que la supresión de la vegetación natural causó cambios significativos en la hidrología de la cuenca. Por ejemplo, se observó un aumento (disminución) en la escorrentía de la superficie en temporada húmeda (seca) en la mayoría de las subcuencas de la CARP. Además, las simulaciones revelaron una reducción en la evapotranspiración real y un aumento en la humedad del suelo en temporada anual y húmeda. En consecuencia, los principales ríos de la cuenca presentaron un aumento (disminución) en su descarga en periodos de lluvia (secos). Este estudio también abordó la comparación entre el UCT de un período prístino (alrededor del año 1500), 1960 y 1985, y los cambios en la precipitación antes y después de la alteración climática. En este caso, los resultados mostraron que el evento de alteración climática de 1970 presentó un mayor efecto sobre los cambios en la descarga anual promedio en la desembocadura de la CARP. Esta investigación presenta una mejor comprensión de los efectos de los CUCT y los cambios en los patrones de precipitación sobre la hidrología de la CARP. Los resultados presentados proporcionan información para mejorar la gestión sostenible de los recursos hídricos.

Palabras clave: descarga, modelo SWAT, análisis de tendencia, modelación en gran escala.

الملخص

يخضع حوض نهر بارانا العلوي لتغيرات واسعة في استخدام الأراضي وتغطيتها في العقود الأخيرة نتيجة النمو السكاني والتنمية الاقتصادية المتسارعة. علاوة على ذلك ، لقد لوحظ تباين في أنماط هطول الأمطار عبر حوض النهر بشكل رئيسي بعد تغير على المناخ في سبعينيات القرن الخالي. وفي الوقت نفسه ، لقد ساهم حوض النهرفي احداث تغييرات كبيرة في المياه السطحية. وفي هذا السياق ، تأتي هذه الدراسة (رساله الدكتوراه) لتبحث في هذه التغيرات الحاصله في هطول الأمطار واستخدام الأراضي والتغطية وآثارها على العمليات الهيدرولوجية في هذا الحوض. لقد تم تقييم الترددات المشاهدة في هطولات الامطار الغزيره في الفترة بين عام 1977 ولغاية 2016 باستخدام اختبار مان - كيندال. ايضا، لقد تم اجراء دراسة نمذجة رقمية للعديد من السيناريوهات باستخدام نموذج أداة تقييم التربة والمياه (SWAT).

لقد تم معايرة النموذج والتحقق من صحته من خلال الاداء المقبول للانهار الرئيسية خلال الفترة ما بين الاعوام 1984 ولغاية 2015 مع الأخذ بعين الاعتباراستخدامات الاراضي وتغطيتها من عام 2015.

اظهرت النتائج أن الأجزاء الجنوبية (الشمالية) من الحوض شهدت ترددات متزايدة (متناقصة) في كميات هطول الأمطار. بالإضافة إلى ذلك ، اظهرت نتائج المناطق الجنوبية (الشمالية) من حوض النهر إلى زيادة في عدد العواصف المطيرة (> 50 مم) وفي أكبر هطول سنوي إجمالي لمدة 5 أيام (عدد الأيام الجافة <1 مم). كما أظهرت النتائج أن الحوض يشهد موسمًا مطيرًا متزايدًا.من خلال مقارنة الغطاء النباتي واستخدامات الاراضي في الحوض في الفترة ما بين عام 1985 ولغاية 2015 ، أظهرت المحاكاة والنمذجه الرقمية أن غياب الغطاء النباتي الطبيعي تسبب في تغييرات كبيرة في هيدرولوجيا الحوض.على سبيل المثال ، لوحظ زيادة (نقصان) الجريان السطحي في الموسم الرطب (الجاف) في معظم انهار ألحواض الفرعية. بالإضافة إلى ذلك ، كشفت عمليات المحاكاة والنمذجه عن انخفاض في التبخر الفعلي وزيادة في رطوبة التربة في الموسم السنوي الرطب. ونتيجة لذلك ، شهدت معظم الأنهار الرئيسية للحوض زيادة (نقصان) في تصريفها في الفترة الرطبة (الجافة).

لقد تناولت هذه الدراسة أيضا المقارنة بين الغطاء النباتي واستخدامات الاراضي في الفترات السابقة (حوالي عام 1500) ، وفترة الدراسة الحالية ما بين عام 1960 ولغاية 1985 ، والتغيرات في هطول

الأمطار قبل وبعد بدء تغير المناخ. وفي هذه الحالة ، أظهرت النتائج أن حدث تحول المناخ كان له تأثير أعلى على التغيرات في متوسط التصريف السنوي في أكبر أنهارالحوض.

يقدم هذا العمل فهمًا أفضل لتأثيرات الغطاء النباتي واستخدامات الاراضي والتغيرات في أنماط هطول الأمطار على الجريان في الحوض. وعلية ، النتائج المقدمه في هذه الرسالة يمكن اعتبارها جزء من عملية تحسين الإدارة المستدامة لموارد المياه في المنطقة.

الكلمات المفتاحية: الجريان. SWAT؛ النمذجة الموسعه.

Papers

Appended papers

I. **Abou Rafee, S.A.,** Freitas, E.D., Martins, J.A., Martins,L.D., Domingues, L.M., Nascimento, J.M., Machado,C.B., Santos, E.B., Rudke, A.P., Fujita, T., Souza, R.A., Hallak, R., Uvo, C.B., 2020: Spatial Trends of Extreme Precipitation Events in the Paraná River Basin. *Journal of Applied Meteorology and Climatology*, v. 59, n. 3, p. 443 – 454. https://doi.org/10.1175/JAMC-D-19-0181.1

II. **Abou Rafee, S.A.,** Uvo, C.B., Martins, J.A., Domingues, L.M., Rudke, A.P., Fujita, T., Freitas, E.D., 2019. Large-scale hydrological modelling of the Upper Paraná River Basin. *Water (Switzerland)*, v. 11, n. 5, p. 882. https://doi.org/10.3390/w11050882

III. **Abou Rafee, S.A.,** Freitas, E.D., Martins, J.A., Machado, C.B., Uvo, C.B., 2020. Hydrologic Response to Large-Scale Land Use and Cover Changes in the Upper Paraná River Basin between 1985 and 2015. *Water Resources Management* (Submitted 2020-08-25).

IV. **Abou Rafee, S.A.,** Uvo, C.B., Martins, J.A., Machado, C.B., Freitas, E.D., 2020. Land Use and Cover Changes versus Climate Shift: Who is the main player in river discharge? - A case study in the Upper Paraná River Basin. (Manuscript).

Author's contribution to the appended papers

I. The author collected all the data, did all the statistical analysis and wrote the major part of the manuscript. The co-authors contributed to the analysis and discussions of the results, and wrote minor parts of the manuscript.

II. The author collected the major part of the data, performed all the numerical simulation and statistical analysis, and wrote the major part of the manuscript. The co-authors collected minor parts of the data, contributed in discussion and wrote minor parts of the manuscript.

III. The author collected the major part of the data, performed all the numerical simulation and wrote all the sections of the manuscript. The co-authors participated in discussion of the results.

IV. The author collected the major part of the data, performed all the numerical simulations and worte all the sections of the manuscript. The co-authors participated in the construction of the scenarios and discussion of the reuslts.

Related Publications not included

Journal Papers

I. Rudke, A.P., Fujita, T., Almeida, D.S. de, Eiras, M.M., Xavier, A.C.F., **Abou Rafee, S.A.,** Santos, E.B., Morais, M.V.B. de, Martins, L.D., Souza, R.V.A. de, Souza, R.A.F., Hallak, R., Freitas, E.D. de, Uvo, C.B., Martins, J.A., 2019. Land cover data of Upper Parana River Basin, South America, at high spatial resolution. Int. *International Journal of Applied Earth Observation and Geoinformation,* v. 83, p. 101926. https://doi.org/10.1016/j.jag.2019.101926

II. Xavier, A.C.F., Rudke, A.P., Fujita, T., Blain, G.C., de Morais, M.V.B., de Almeida, D.S., **Abou Rafee, S.A.,** Martins, L.D., de Souza, R.A.F., de Freitas, E.D., Martins, J.A., 2020. Stationary and non-stationary detection of extreme precipitation events and trends of average precipitation from 1980 to 2010 in the Paraná River basin, Brazil. *International Journal of Climatology*, v. 40, n. 2, p. 1197 – 1212. https://doi.org/10.1002/joc.6265

Conferences and workshops

I. **Abou Rafee**, **S. A.,** Xavier, A. C. F., Rudke A. P., Fujita, T., Brand, V. S., Morais, M. V. B., Basso, J. L. M., Santos, E. B., Martins, L. D., Souza, R. A. F., Hallak, R., Martins, J. A., Freitas, E. D., 2016. Análise de tendência de vazão e precipitação da bacia do rio Tietê. *XIX Congresso Brasileiro de Meteorologia, João Pessoa – PB, Brazil.*

II. Rudke, A. P., Fujita, T., Xavier, A. C. F., Morais, M. V. B., Brand, V. S., **Abou Rafee, S. A.,** Martins, L. D., Souza, R. A. F., Freitas, E. D., Martins, J. A., 2016. Avaliação de produtos globais de uso e ocupação do solo para a bacia do Rio Paraná. *XIX Congresso Brasileiro de Meteorologia, João Pessoa – PB, Brazil.*

III. Santos, E. B., **Abou Rafe, S. A.,** Morais, M. V. B., Martins, L. D., Souza, R. A. F., Hallak, R., Martins, J. A., Freitas, E. D., 2016. Análise de eventos extremos de precipitação na bacia do Rio Iguaçu- Paraná. *XIX Congresso*

Brasileiro de Meteorologia, João Pessoa – PB, Brazil.

IV. Fujita, T., Rudke, A. P., Xavier, A. C. F., Morias, M. V. B., Brand, V. S., **Abou Rafee, S. A.,** Freitas, E. D., Souza, R. A. F., Martins, J. A., 2016. Aplicação de técnicas de Krigagem e IDW na espacialização de dados de precipitação na bacia do rio Paraná *XIX Congresso Brasileiro de Meteorologia, João Pessoa – PB, Brazil.*

V. Santos, E. B., **Abou Rafee, S. A.,** Martins, L. D., Souza, R. A. F., Hallak, R., Martins, J. A., Freitas, E. D., 2017 . Influência do El Niño Oscilação Sul sobre o Regime de Chuvas na Bacia do Rio Paraná. *Simpósio Internacional de Climatologia, Petrópolis - Rio de Janeiro, Brazil.*

VI. **Abou Rafee, S.A.,** Rudke, A. P., Fujita, T., Morais, M. V. B., Santos, E. B., Hallak, R., Souza, R. A. F., Martins, L. D., Martins, J. A., Freitas, E. D., 2017. Analysis of spatial distribution of observed ground-based data and large scale modelling of the Parana River Basin. *2017 International SWAT Conference, Warsaw, Poland.*

VII. Fujita, T., Rudke, A. P., Morais, M. V. B., **Abou Rafee, S.A.,** Souza, R. A. F., Souza, R. V. A., Freitas, E. D., Martins, L. D., Martins, J. A., 2017. Response of Randomized Subsets of Rainfall Gauges Over a Paraná River Sub-basin. *2017 International SWAT Conference, Warsaw, Poland.*

VIII. Rudke, A. P., Fujita, T., Morias, M. V. B., **Abou Rafee, S.A.,** Souza, R. A. F., Souza, R. V. A., Freitas, E. D., Martins, L. D., Martins, J. A., 2017. Hydrological Response of a Brazilian Catchment to Different Land Use and Land Cover Products. *2017 International SWAT Conference, Warsaw, Poland.*

IX. Santos, E. B., Freitas, E. D., **Abou Rafee, S.A.,** Fujita, T., Rudke, A. P., Martins, J. A., Martins, L. D., Hallak, R.; Souza, R. A. F., 2018. The Relationships Between El Niño Southern Oscillation and Climate Extremes in Paraná River Basin, Brazil. *American Meteorology Society, Austin, TX, United States.*

X. **Abou Rafee, S.A.,** Freitas, E.D., Martins, J. A., Machado, C., Rudke, A. P., Fujita, T., Uvo, C. B., 2019. Hydrologic response to land use changes in the Upper Paraná River Basin. *The Inaugural International Symposium on Water Modelling (iSymWater2019), Beijing, China.*

XI. Freitas, E. D., **Abou Rafee, S.A.,** Fujita, T., Xavier, A. C. F., Machado, C., Campos, T. L. O. B. , Martins, L. D. , Uvo, C. B., Souza, R. A. F., Santos,

E. B., Hallak, R., Morais, M. V. B., Martins, J. A., 2019 . Effects of climate change and land use on the hydrology of the Paraná River Basin - Brazil. *Sixth International Soil and Water Assessment Tool, South East and East Asia Conference, Seam Reap, Cambodia*.

XII. Martins, J. A., Rudke, A. P., **Abou Rafee, S.A.,** Fujita, T., Xaveir, A. C. F., Machado, C., Martins, L. D., Campos, T. L. O. B., UVO, C. B., Freitas, E. D., 2019. Land cover dynamics by agricultural activities over the Upper Paraná River Basin. *Sixth International Soil and Water Assessment Tool, South East and East Asia Conference, Seam Reap, Cambodia.*

XIII. **Abou Rafee, S.A.,** Uvo, C. B., Martins, J. A., Freitas, E.D., 2019. Assessing the hydrologic impacts of land use change in the Upper Paraná River Basin between 1985 and 2015. *Sixth International Soil and Water Assessment Tool, South East and East Asia Conference, Seam Reap, Cambodia.*

XIV. Machado, C., **Abou Rafee, S. A.,** Freitas, E. D., 2019. Future land use and land cover simulation and analysis of extreme rainfall events in an important Brazilian hydrographic basin: a support to regional atmospheric modeling. *2019 AGU Fall Meeting, São Francisco, United States.*

XV. Machado, C.; Campos, T. L. O. B.; **Abou Rafee, S.A.;** Martins, J. A.; Freitas, E. D., 2019. Bacia Hidrográfica do Paraná: Uma análise do regime pluviométrico, eventos extremos e ocupação do solo. *XXIII Simpósio Brasileiro de Recursos Hídricos, Foz do Iguaçu – PR, Brazil.*

Co-supervised Master thesis

I. Nsabimana, B. and Estallo, Utande., 2019. Sustainable Drainage Systems Assessment and Optimisation-A case study for Lussebäcken Catchment, Helsingborg. Master Thesis TVVR-19/5009, Lund University.

List of Figures

List of Tables

List of Abbreviations

ANA	Brazilian National Water Agency
ANEEL	Brazilian Electricity Regulatory Agency
ARS-USDA	Agricultural Research Service of the United States Department of Agriculture
CFSR	Climate Forecast System Reanalysis
CN	Curve Number
DEM	Digital Elevation Model
ECMWF	European Centre for Medium-Range Weather Forecasts
EMBRAPA	Brazilian Agriculture Research Corporation
ENSO	El Niño–Southern Oscillation
HRU	Hydrologic Response Unit
HWSD	Harmonized World Soil Database
IDW	Inverse Distance Weighted
KGE	Kling-Gupta efficiency
LAI	Leaf Area Index
LUC	Land Use and Cover
LUCC	Land Use and Cover Changes
MCS	Mesoscale Convective Systems
MK	Mann–Kendall
NSE	Nash-Sutcliffe efficiency

ONS	Brazilian National Electrical System Operator
PBIAS	Percent Bias
PDO	Pacific Decadal Oscillation
pint	Annual mean precipitation per rain days ($\geq 1\ mm\ day^{-1}$)
pn50	Annual number of days with precipitation $>\ 50\ mm\ day^{-1}$
px5d	Annual greatest 5-day total precipitation
pxcdd	Annual maximum number of consecutive dry days ($< 1\ mm\ day^{-1}$)
R^2	Coefficient of Determination
RSR	Root mean Square Error
SACZ	South Atlantic Convergence Zone
SALLJ	South American Low-Level Jet
SAMS	South American Monsoon System
SNHT	Standard Normal Homogeneity Test
SRTM	Shuttle Radar Topography Mission
SUFI-2	Sequential Uncertainty Fitting
SWAT	Soil and Water Assessment Tool
SWAT-CUP	Soil and Water Assessment Tool Calibration and Uncertainty Program
UPRB	Upper Paraná River Basin

1. Introduction

1.1 Motivation

The Upper Paraná River Basin (UPRB) is part of the second largest and most socio-economically important river basins in South America, the La Plata River Basin. The UPRB plays a significant role in the economic activity and development of Brazil, being a home of more than 65 million inhabitants, of whom 93% live in urban areas (IBGE, 2019). The basin is being responsible for the most extensive livestock, agricultural and biofuel production, transportation of products, and hydroelectricity generation. According to the Brazilian National Water Agency (ANA), the UPRB has the largest water consumption mostly used for agriculture and industrial activities. Besides, the basin has the highest hydroelectric power generation capacity in South America. As reported by the Brazilian Electricity Regulatory Agency (ANEEL, 2020), more than 62% of electricity in Brazil is generated by hydropower plants, which almost 40% are provided from the basin. Currently, the UPRB houses 156 large hydropower plants (with a capacity of more than 30 MW) that provide about 52,000 MW (Figure 1). Also, the basin houses 595 small hydropower plants (capacity between 1.1 MW and 30 MW) and 214 micro hydropower plants (capacity up to 1 MW) which provide 7,074 MW and 193 MW, respectively.

Land Use and Cover Changes (LUCC) is one of the main factors that affect the hydrological processes within watersheds (DeFries & Eshleman, 2004, Francesconi *et al.*, 2016). In the latest decades, the UPRB has undergone extensive LUCC due to rapid population growth and economic development. Rudke (2018) observed significant natural vegetation suppression over the basin between 1985 and 2015. For instance, cerrado (Brazilian savanna) had a reduction of about 173×10^3 km^2 that were mostly concentrated in the central-western and northern parts of the basin. Also, the Brazilian Ministry of the Environment reported deforestation of 76% of the Atlantic forest biome and 49% of the cerrado (MMA, 2011, 2012). Particularly, Paraná and São Paulo states, located in the east of the basin, have lost more than 70% of their primitive forests, while the original vegetation in the western part of the basin, was maintained until the 1970s when the development of agri-business increased. Deforestation occurred for different objectives, but in most cases, natural vegetation was replaced by cropland and grassland areas (Tucci, 2002). Concurrently, significant changes in hydrology have been presented over the UPRB (Antico *et al.*, 2016, Bayer, 2014, Camilloni & Barros, 2003, Lee *et al.*, 2018, Tucci, 2002, Tucci & Clarke, 1998).

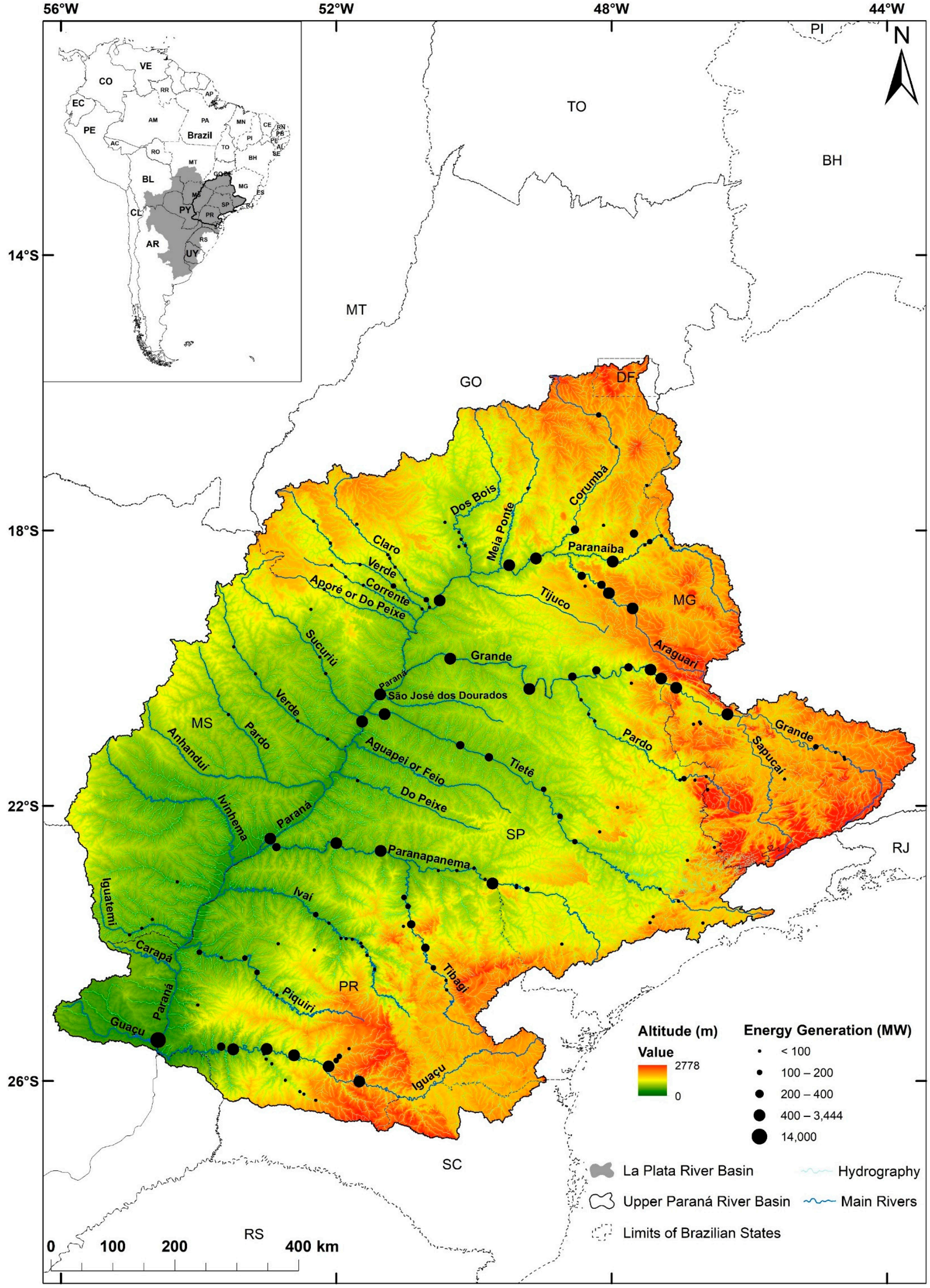

Figure 1. Location of the UPRB showing the topographic patterns, hydrography, and the spatial distribution of the largest hydropower plants (installed or planned with a capacity of more than 30 MW).

In addition to the LUCC, the 1970s climate shift (Jacques-Coper & Garreaud, 2015) is pointed out as one of the main events that led to a variation in precipitation patterns over the URPB that consequently could have affected the basin hydrology. The impacts of the climate shift on precipitation has been investigated over North American (Hartmann & Wendler, 2005, Litzow, 2006) and South American (Agosta & Compagnucci, 2008; Jacques-Coper and Garreaud, 2015) regions, and considered by the researchers as an unprecedented event. Climate shift is defined as the short period when several climate oscillations such as Pacific Decadal Oscillation (PDO) and El Niño–Southern Oscillation (ENSO) changed phases, out of which could lead the climate system to a new state (Jacques-Coper & Garreaud, 2015, Meehl *et al.*, 2009, Tsonis *et al.*, 2007, Wang *et al.*, 2009, Yuan Zhang *et al.*, 1997). During the 1970s climate shift, a cold to warm sea surface temperature shift in the tropical pacific was observed. Thereby, it induced an increase in annual mean precipitation in southernmost areas of South America (Jacques-Coper & Garreaud, 2015).

1.2 Research objective

Under such a perspective of the issues discussed in the previous section, this research aims to investigate the changes in precipitation and LUCC and their effects on the hydrological processes in the UPRB. Hence, the thesis intended to fill the gaps by answering the following questions:

- *Are there any trends of seasonal, annual, and extreme precipitation events in the UPRB?*

- *What are the hydrologic responses to land use and cover changes occurred in the latest decades in the UPRB?*

- *To which extent are changes observed on land use and cover, and changes observed on precipitation due to climate shift responsible for the increase in the discharge of the Paraná River?*

To achieve these questions, the specific objectives were:

I. To investigate the behavior of the precipitation trend and climate shift in the UPRB;

II. To set up the SWAT model with the most appropriate dataset available;

III. To calibrate and validate the SWAT model for the main rivers of the UPRB;

IV. To prepare the Land Use and Cover (LUC) and climate shift scenarios;

V. To identify the changes in LUC and precipitation patterns over the basin;

VI. To simulate the scenarios constructed;

VII. To quantify the potential impacts of LUCC and climate shift scenarios.

1.3 Thesis Structure

This thesis is based on a summary that is connected to the research presented and discussed in the four appended papers, out of which two are published, one is under review, and one is to submitted. Paper I, **Spatial trends of extreme precipitation events in the Paraná River Basin**, analyses the spatial trends performed on annual and seasonal precipitation totals as well as for the extreme precipitation indicators at 853 stations from 1977 to 2016. Paper II, **Large-Scale Hydrological Modelling of the Upper Paraná River Basin,** presents the hydrological modelling and the performance of the main rivers of the UPRB using the Soil and Water Assessment Tool (SWAT) model during the period 1984 – 2015. Paper III, **Hydrologic Response to Large-Scale Land Use and Cover Changes in the Upper Paraná River Basin between 1985 and 2015,** estimates the impacts of LUCC between 1985 and 2015 on soil moisture, actual evapotranspiration, surface runoff, and discharge in the UPRB examined for annual, wet, and dry season. Paper IV, **Land Use and Cover Changes versus Climate Shift: Who is the main player in river discharge? A case study in the Upper Paraná River Basin**, addresses the main causes for the increased annual discharge of the Lower Paraná river by simulating three different LUC from the pristine period (around the Year 1500), 1960 and 1985, during the precipitation period 1961 – 1990.

The remainder of this summary is structured as follows. First, an introduction presents the motivation and research objective of this thesis. Then, chapter two starts with a brief description of the study area. The data preparation and the methods used for trend analysis and hydrological modelling are also described in this chapter. Furthermore, the strategies of the construction of the scenarios are presented. In chapter three, the main results from the appended papers are summarized and discussed. Finally, the main conclusions and future work are presented in chapter four.

2. Material and Methods

Different methods and data were used in this thesis. This chapter provides a brief description of the data prepared and the numerical scenarios constructed, which were used for the statistical analysis and hydrological modelling. For further details, the reader is referred to the appended papers.

2.1 Study area

The study area of this thesis covers the UPRB located in the central-southern region of Brazil (Figure 1). It is situated between the coordinates 26° 51′ 23.35″ and 15° 27′ 25.54″ S latitude, and 56° 7′ 4.61″ and 43° 34′ 50.61″ W longitude. The basin has a drainage area of 900,480 km^2 and altitude varying from 78 up to 2778 meters above sea level. It covers six Brazilian states: São Paulo (23.5%), Paraná (20.4%), Mato Grosso do Sul (18.9%), Minas Gerais (17.6%), Goiás (15.7%), Santa Catarina (1.2%), and the Federal District (0.4%), and also includes a small portion of Paraguay (2.3%).

Several synoptic systems affect the UPRB which causes a different amount of precipitation across the basin. In the northern part of the basin under the influence of the South American Monsoon System (SAMS) (Carvalho *et al.*, 2011, Grimm *et al.*, 2007, Marengo *et al.*, 2012) has dry winters (< 30 mm), and wet summers (> 800 mm) (Abou Rafee *et al.*, 2020). On the other hand, the precipitation over the southern part of the UPRB is spread over seasons ranging from 240 (winter) to 500 mm (summer) (Abou Rafee *et al.*, 2020). The precipitation in the southern parts of UPRB is associated with different systems such as Mesoscale Convective Systems (MCS), South American Low-Level Jet (SALLJ), the passage of cold fronts, and the South Atlantic Convergence Zone (SACZ) (Carvalho *et al.*, 2004, Morales Rodriguez *et al.*, 2010, Velasco & Fritsch, 1987).

2.2 Precipitation trends

2.2.1 Data quality control and precipitation indices

Daily precipitation data were collected from the Brazilian National Water Agency (ANA). The trend analysis was applied for the dataset from 1977 to 2016. The stations were selected when the following conditions are met: 1) First, double records and typo errors were verified. Consecutive repeated values above 1 mm day^{-1} and precipitation above 250 mm day^{-1} were considered as missing data, 2) Then, stations series with less than 10% of missing data were selected, and finally 3) Data series that presented nonhomogeneity were disregarded. The homogeneity was checked by the Standard Normal Homogeneity Test (SNHT) (Alexandersson, 1986). As a result, a total of 853-gauge stations were selected (Figure 2). After this step, series were created according to the precipitation indices presented in Table 1.

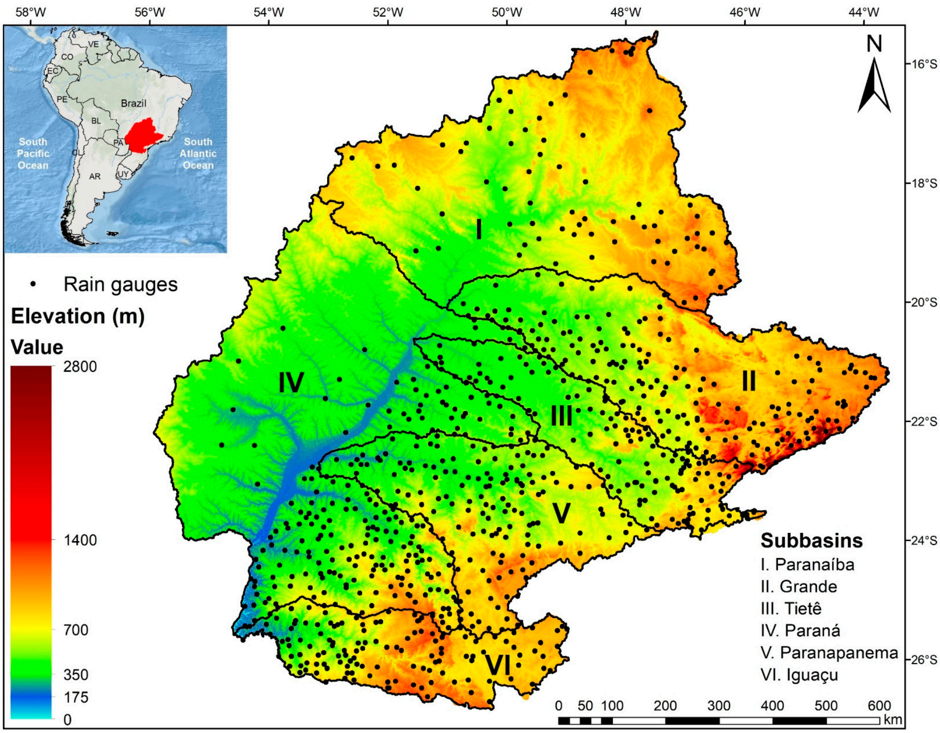

Figure 2. Geographic location and topographic map of the UPRB with its subbasins showing the spatial distribution of the 853 rain gauges.

From Abou Rafee *et al.* (2020).

Table 1. List of precipitation indices selected.

Based on Abou Rafee *et al.* (2020).

Indices	Definition	Unit
Accumulated precipitation totals	Annual Summer (December, January, and February) Autumn (March, April, and May) Winter (June, July, and August) Spring (September, October, and November)	mm
5-day maximum precipitation (px5d)	Annual greatest 5-day total precipitation	mm
Simple daily intensity (pint)	Annual mean precipitation per rain day ($\geq 1\ mm\ day^{-1}$)	$mm\ day^{-1}$
Longest dry period (pxcdd)	Annual maximum number of consecutive dry days ($< 1\ mm\ day^{-1}$)	$days$
Rainstorm days (pn50)	Annual number of days with precipitation $> 50\ mm\ day^{-1}$	$days$

2.2.2 Trend analysis

Trends were investigated by using the nonparametric statistical Mann-Kendall (MK) test (Kendall, 1975, Mann, 1945). To avoid misleading trend detection by missing data, the following criteria were not considered in the trend analysis: i) years with more than 14 missing data, and ii) seasonal totals (3 months) with more than 3 missing data. The statistical evidence against the null hypothesis was evaluated through the bootstrap method (Efron, 1979) by using 500 random samples. It was considered statistically significant if the resampled series trend falls into the upper or lower 5% of the bootstrapped distribution.

To assess the spatial distribution of the values of trends, the climatological mean of the precipitation indices (Table 1) were interpolated using the Inverse Distance Weighted (IDW) method.

2.3 Hydrological modelling of the UPRB

2.3.1 SWAT model

The hydrological simulations of the UPRB were estimated using the 2012 version of the Soil and Water Assessment Tool (SWAT) model with an ArcGIS interface (Arnold *et al.*, 1998, https://swat.tamu.edu). SWAT is an open source, semi-distributed, and physically based model developed by the Agricultural Research Service of the United States Department of Agriculture (ARS-USDA). The model can be used to design analyses related to physical processes, both small (Ferrant *et al.*, 2011) and large-scale (Abou Rafee *et al.*, 2019, Rajib & Merwade, 2017), and can be executed in a continuous simulation in monthly or daily time steps. It has been extensively applied for different approaches such as climate change (Ficklin *et al.*, 2009), LUCC (Chotpantarat & Boonkaewwan, 2018), and climate variability scenarios (Wu & Johnston, 2007). Based on the topography, a basin is discretized into subbasins, which are connected by a stream network. To assess the differences in LUC and the heterogeneous soil in a watershed, each subbasin is further discretized into Hydrologic Response Units (HRUs), according to unique combinations of LUC, soil type, and slopes. For each HRU, simulated hydrological processes, such as surface runoff and evapotranspiration, are generated separately, and then routed through the river network to the outlet of the basin. For a further detailed description of the SWAT model, the reader is referred to Neitsch *et al.* (2011).

The hydrological behavior of a river basin in the SWAT model is based on the water balance equation (1):

$$\boldsymbol{SW_t = SW_o + \sum_{i=1}^{n}(P_{T_i} - E_{sup_i} - ET_i - E_{Lat_i} - E_{sub_i})} \quad (1)$$

where SW_t e SW_o are the final and initial water content on day i (mm), and P_{T_i}, E_{sup_i}, ET_i, E_{Lat_i}, and E_{sub_i} are the amount of precipitation, surface runoff, actual evapotranspiration, subsurface lateral flow, and base flow, respectively, on day i (mm).

2.3.1.1 Data description

Different input data are required to build a hydrological project with SWAT, which includes climatic, hydrologic, and physical variables. This section intends to describe the processes used to manipulate and organize the data, which was one of the important steps of this research project. An overview of the data used is given in Table 2 and Figure 3.

2.3.1.1.1 Climatic

The daily climatic data were prepared for the period simulation from 1979 to 2015, with the first five years used for the warming up of the model (1979 – 1983), the following 21 years for its calibration (1984 – 2004), and the last 11 years for its validation (2005 – 2015). Due to the low spatial-temporal resolution of observed data pertaining to temperature, solar radiation, relative humidity, and wind speed, the gridded daily meteorological data obtained from the National Center for Environmental Prediction— Climate Forecast System Reanalysis (CFSR) at 38-km grid spacing were used. The data for total daily precipitation was provided by the ANA, which made available a collection of data from 149 institutions (Figure 3a).

The study area has a good spatial density of stations, with 2,494 rain gauges within the basin. The precipitation data were thoroughly controlled before use. First, quality checks, such as double records, typographical errors, and the location of stations were evaluated. Then, the data were interpolated to a spatial resolution of 0.1 degrees using the IDW method.

2.3.1.1.2 Topography

For topographic data, a Digital Elevation Model (DEM) at a 90-meter resolution obtained from the Shuttle Radar Topography Mission (SRTM) (available at http://srtm.csi.cgiar.org/srtmdata/) was used (Figure 3b). Based on this data, the digital river network, as well as the subbasins, were generated.

2.3.1.1.3 Soil

The soil map was elaborated from the information provided by the Brazilian Agriculture Research Corporation (EMBRAPA) at a scale of 1:5,000,000. For the Paraguayan portion of the basin, the Harmonized World Soil Database (HWSD) with a spatial resolution of $1\ km \times 1\ km$ was used. In this study, the characteristics of oligotropic, mesotropic, eutropic, and dystropic soils were grouped in a single class, resulting in 15 classes (Figure 3c). The properties of each soil class were collected from a diverse set of documents that used the SWAT model in Brazilian basins (Fauconnier, 2017, Mercuri *et al.*, 2009, Pereira, 2013).

2.3.1.1.4 Land Use and Cover

LUC data were obtained from Rudke (2018) and Rudke *et al.* (2019). The map was generated using pixel-based image classifiers, with the Support Vector Machine (SVM) algorithm. Overall, most of the basin regions presented agreement between the classified LUC and observed data, ranging from satisfactory (0.6 – 0.8) to good (0.8 – 1.0) of Kappa coefficient and global accuracy. The original classification of 10 different categories was reclassified into six major classes: forest, cropland, grassland, water, cerrado (Brazilian savanna), and urban areas (Figure 3d).

2.3.1.1.5 River discharge

To evaluate the performance of the model, monthly river discharge data were organized based on the calibration period (1984 – 2004) and validation the period (2005 – 2015). The data comprise both natural streamflow data, derived from ANA, and naturalized discharges, obtained from the National Electrical System Operator (ONS).

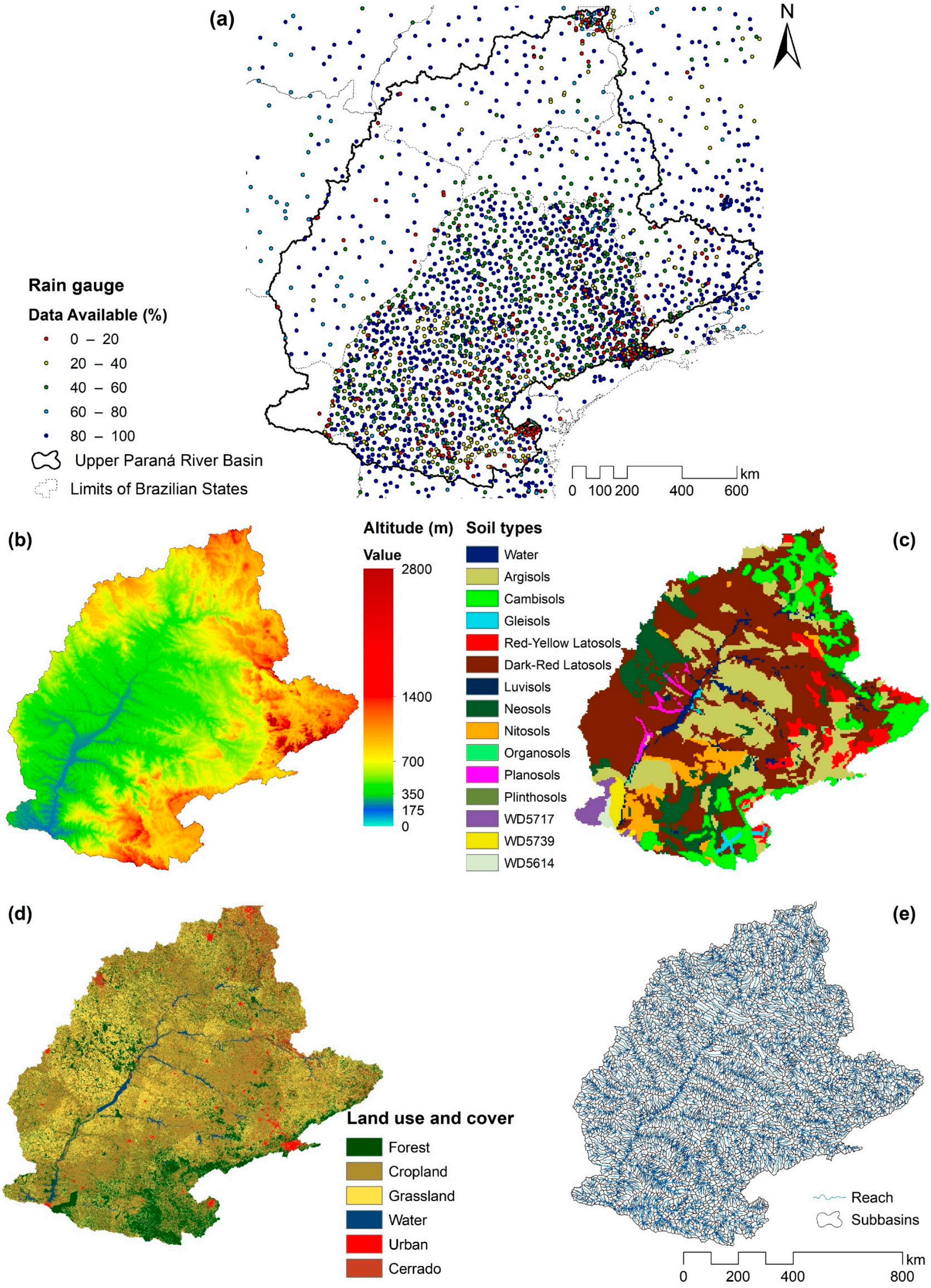

Figure 3. Maps of the (a) spatial distribution of precipitation stations, (b) topography, (c) soil types, (d) Land use and cover, and (e) discretization and reaches of the UPRB.

Based on Abou Rafee *et al.* (2019).

Table 2. Overview of the model input data.

Data	Description	Source
Topography	90-meter resolution Digital Elevation Model (DEM)	Shuttle Radar Topography Mission (SRTM) (http://srtm.csi.cgiar.org/srtmdata/)
Land use and cover	30-meter resolution classification	(Rudke, 2018, Rudke et al., 2019)
Soil	Derived from 1:5000000 scale digital map	Brazilian Agriculture Research Corporation (EMBRAPA) (https://www.embrapa.br/solos/sibcs/solos-do-brasil) Harmonized World Soil Database (HWSD) (http://www.fao.org/nr/land/soils/)
Precipitation	Daily (1979 – 2015)	Brazilian National Water Agency (ANA) (http://www.snirh.gov.br/hidroweb)
Maximum and minimum temperature; relative humidity; wind speed; and solar radiation	Daily (1979 – 2015)	Climate Forecast System Reanalysis (CFSR) (https://globalweather.tamu.edu)
River Discharge	Monthly (1984 – 2015)	Brazilian National Water Agency (ANA) (http://www.snirh.gov.br/hidroweb) Brazilian National Electrical System Operator (ONS) (http://www.ons.org.br)

2.3.1.2 Model set up

SWAT model project for the UPRB was built with the highest possible spatial discretization. The slopes were divided into five classes ranging between 0 – 3%, 3 – 8%, 8 – 20%, 20 – 45%, and > 45%. The basin was discretized into 5,187 sub-watersheds, using a threshold drainage area of 100 km^2, with an average size of about 173 km^2 (see Figure 3e). To represent the spatial heterogeneity across the UPRB, these subbasins were further divided into 44,635 HRUs using a defined threshold of 5% for LUC, 10% for soil, and 20% for slope. The Soil Conservation Service curve number (CN) (USDA Soil Conservation Service, 1972) and the Penman-Monteith (Monteith J. L., 1965) methods were used to compute the surface runoff and potential evapotranspiration, respectively. For groundwater flow, SWAT simulates two types of aquifers: shallow (unconfined) aquifers, which contribute to return flow to streams within the catchment, and deep (confined) aquifers, which are responsible for the flow outside the basin (amount of water used, for example, for irrigation and water supply) and are considered water sinks in the system (Neitsch *et al.*, 2011).

2.3.1.3 Calibration and validation process

2.3.1.3.1 SUFI2 and parameter calibration

The calibration was performed by the Sequential Uncertainty Fitting (SUFI-2) algorithm proposed by Abbaspour *et al.* (2004), using SWAT-CUP version 5.1.6.2 (Soil and Water Assessment Tool Calibration and Uncertainty Program, Abbaspour, 2015). Moreover, to optimize the model execution, the parallel processing module (Rouholahnejad *et al.*, 2012) was used. SUFI-2 was developed by considering the uncertainties of parameter ranges, which are sampled through Latin hypercube sampling. Table 3 shows the list of parameters as well as their ranges used in the calibration process of the discharge series.

In addition, manual calibration to adjust the Leaf Area Index (LAI) curve for forest, cerrado, and pasture using the modified plant growth module provided by Strauch and Volk, (2013) was used. Although SWAT has been applied for tropical basins, previous studies reported that its plant growth module is not suitable in a system that has perennial tropical vegetation since the model was originally designed for temperate areas (Alemayehu *et al.*, 2017, Van Griensven *et al.*, 2012, Strauch & Volk, 2013, Wagner *et al.*, 2011)

2.3.1.3.2 Performance evaluation

To assess the performance of the model, it is recommended that the simulation should be evaluated by several statistical indices (Arnold *et al.*, 1998). Five indices were chosen so that they, together, can provide a general overview of the quality of the simulations. The percent bias (PBIAS) (Yapo *et al.*, 1996), coefficient of determination (R^2), Nash-Sutcliffe efficiency (NSE) (Nash & Sutcliffe, 1970), The Kling-Gupta efficiency (KGE) (Gupta *et al.*, 2009), and the root mean square error (RSR) (Moriasi et al., 2007) were selected.

Table 3. List of sensitive parameters selected for calibration.

Based on Abou Rafee *et al.* (2019).

Parameter *	Description	Initial Range	
		Min	Max
From Soil			
r_CN2.mgt	SCS runoff curve number	−0.4	0.4
r_SOL_AWC.sol	Soil available water storage Capacity (mm H_2O mm soil^{-1})	−0.4	0.4
r_SOL_K.sol	Saturated hydraulic conductivity (mm h^{-1})	−0.8	0.8
r_ESCO.hru	Soil evaporation compensation factor	−0.4	0.4
r_OV_N.hru	Manning´s n value for overland flow	−0.4	0.4
Groundwater			
r_GWQMIN.gw	Threshold depth of water in the shallow aquifer for return flow (mm)	−0.8	0.8
r_GW_DELAY.gw	Groundwater delay (days)	−0.8	0.8
r_REVAPMN.gw	Threshold depth of water in the shallow aquifer for “revap” (mm)	−0.5	0.5
r_RCHRG_DP.gw	Deep aquifer percolation fraction	−0.5	0.5
r_GW_REVAP.gw	Groundwater “revap” coefficient	−0.4	0.4
r_ALPHA_BF.gw	Base flow alpha factor (days)	−0.8	0.8
r_ALPHA_BNK.rte	Base flow alpha factor for bank storage	−0.5	0.5
Channel			
r_CH_K2.rte	Effective hydraulic conductivity in channel (mm h^{-1})	−0.8	0.8
r_CH_N2.rte	Manning´s value for main channel	−0.8	0.8
Land use and Cover			
r_EPCO.bsn	Plant uptake compensation factor	−0.5	0.5
r_CANMX.hru	Maximum canopy storage (mm H_2O)	−0.4	0.4
Subbasin			
r_SURLAG.bsn	Surface runoff lag time	−0.5	0.5
r_SLSUBBSN.hru	Average slope length (m)	−0.4	0.5
r_ LAT_TTIME.hru	Lateral flow travel time (days)	−0.5	0.5
r_HRU_SLP.hru	Average slope steepness (m m^{-1})	−0.4	0.4

*“r_” refers to a relative change in the parameters where the current value is multiplied by 1 plus a factor from the given parameter range.

2.3.1.3.3. Modelling protocol

The criteria and the procedures used for the calibration processes are summarized as follows:

I. In order to run the simulation with parallel processing, due to memory limitations as a result of the project size, the basin area was divided into 9 watersheds for calibration and the fitted values in each subbasin were used for the initial project (see Figure 4).

II. To avoid the incorrect location of the calibration outlets, its geographic position was verified.

III. A multi-site calibration from upstream to downstream outlets calibration, recommended by Leta *et al.* (2017) for heterogeneous basins was applied.

IV. The discharge outlets which performed satisfactory or better in all statistical indices (listed in Performance evaluation section) were not considered in the calibration process. The subbasins that were not considered in the calibration process are illustrated in black in Figure 4.

V. The initial parameter ranges followed the calibration protocol presented by Abbaspour *et al.* (2015) for large-scale basins. For example, if the simulation presented base flow too low (high), the GWQMN, GW_REVAP, and REVAMPM parameters should increase (decrease). Therefore, before each calibration, the temporal evolution of the discharge simulation was evaluated as to whether it underestimated or overestimated the observation.

VI. The objective function selected in the calibration process was NSE index.

VII. Once the sub-project was built for the subbasin, and the ranges of parameters were defined, the model simulations were run between 150 and 500 times, with a maximum of 3 iterations. The numbers of simulations, as well as of iterations, were based on the size of the sub-project and performance of the initial simulation.

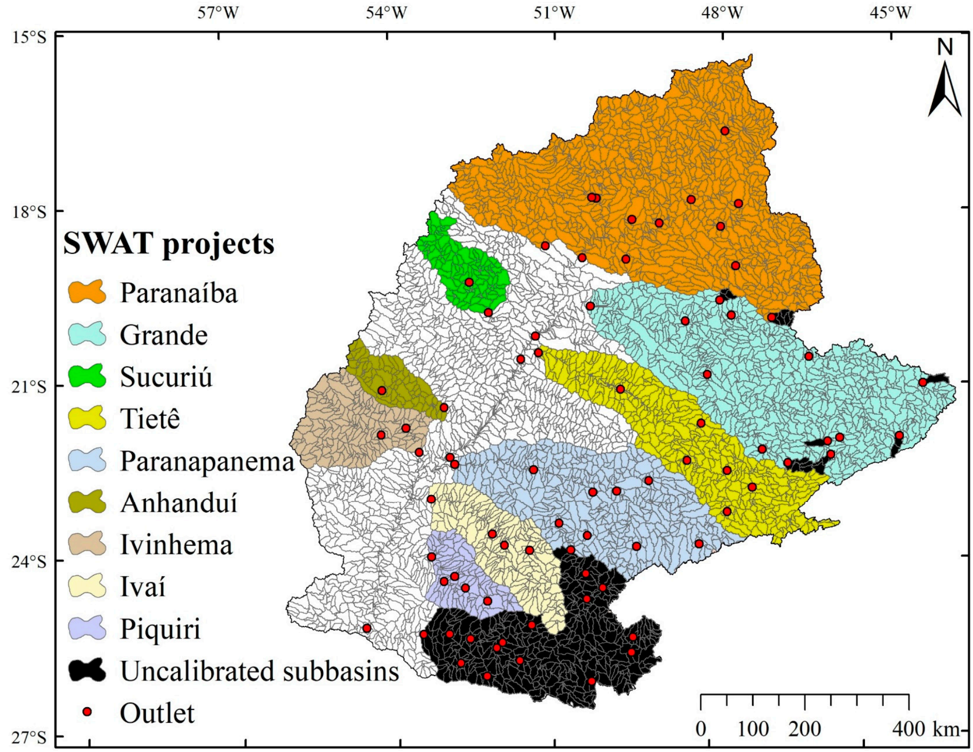

Figure 4. Division of SWAT projects for calibration.

2.4 Numerical scenarios

2.4.1 LUC 1985 versus LUC 2015

2.4.1.1 Data

Two LUC under unchanged climatic conditions were simulated. The LUC correspond to the years 1985 and 2015 (Figure 5) classified by Rudke (2018) and Rudke et al. (2019). The simulations were based on the data and model set up aforementioned (section 2.3). In this case, following the configuration criteria, 44,635 (LUC 2015) and 50,272 (LUC 1985) HRUs were created.

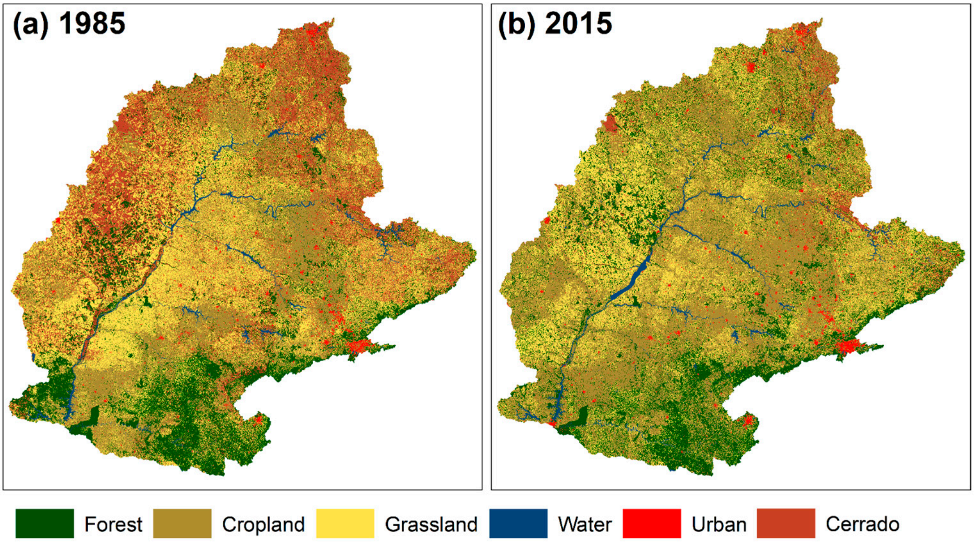

Figure 5. Land use and cover (LUC) classes for 1985 (a) and 2015 (b).

2.4.1.2 Analysis of the effects of LUCC

The effects of LUCC on the hydrologic components under unchanged climatic conditions of the UPRB were evaluated as follows:

I. To address the main LUCC between 1985 and 2015 in the basin, 9 major transitions of four LUC classes were calculated: Cerrado to forest; Grassland to forest; Cropland to forest; Forest to grassland; Cerrado to grassland; Cropland to grassland; Forest to cropland; Cerrado to cropland; and Grassland to cropland.

II. To identify the effects of LUCC on hydrology within the UPRB, the surface runoff, actual evapotranspiration, soil moisture, and discharge were analyzed.

III. The aforementioned hydrologic components were calculated by the relative change for the simulation with the LUC from 2015 relative to the simulation with LUC from 1985. Changes were examined for annual (hydrological year, from October to September), wet (October – March), and dry (April – August) seasons considering the calibrated and validated period from 1984 to 2015.

IV. The hydrological variables were calculated using the 5,187 watersheds discretization of the UPRB, however, the results were illustrated and interpreted for the 34 major subbasins as shown in Figure 6.

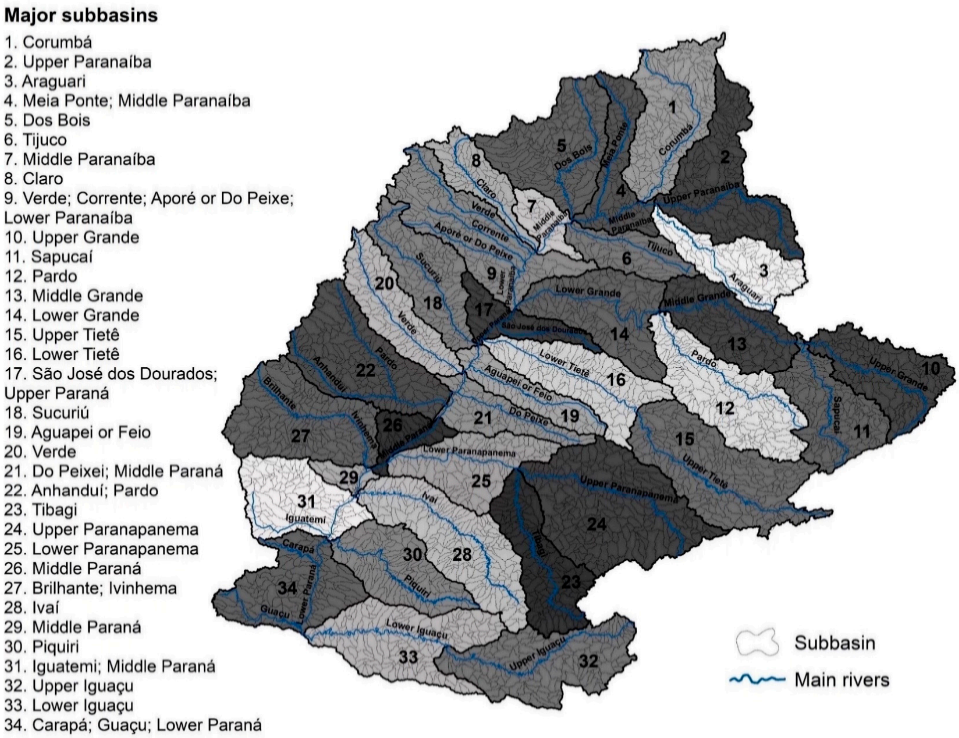

Figure 6. Subbasin discretization, major subbasins and main rivers of the UPRB.

2.4.2 LUCC versus Climate shift

2.4.2.1 Data preparation

2.4.2.1.1 Climatic data

The climatic data were prepared for the simulation period from January 1956 to December 1990, being the first five years used to the warming up of the model (1956 – 1960). Daily maximum and minimum temperature, solar radiation, wind speed, and relative humidity were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis ERA-20C at the grid resolution of 0.25 degrees. Daily precipitation data from the ANA were used. It was provided 2,739 rain gauge stations (2,292 within basin), out of which 38% have less than 20% of missing data. These data were interpolated to a spatial resolution of 0.1 degrees using the IDW method.

2.4.2.1.2. Physical data

Three simulations of discharge were made and scenarios created. Similar to all simulations are the input data of climatic, soil, and topography. A different LUC was used in each simulation. They are a pristine LUC of around 1500, a LUC for 1960 and one for 1985 as follows:

LUC – 1985

The LUC for 1985 was based on the classification made by Rudke (2018). The map was generated from pixel-based classifications, using 50 Landsat-5 scenes. Based on his classification, the UPRB was divided into six major categories: forest, cerrado (Brazilian savanna), cropland, grassland, water, and urban areas.

LUC – T0

A map of the original vegetation, representing the unchanged landscape from a pristine period (around the Year 1500) named in this work as T0 was constructed. The original vegetation vectors were based on the classification performed by the RADAMBRASIL project (IBGE, 2017). This project generated mappings of the 70's and 80's decades, being the first national effort to know the physical and biotic conditions of the national territory using a large amount of material and human resources. The categories of natural vegetation and savanna physiognomies from the T0 map were grouped into a single class as forest and cerrado, respectively. In addition, the water and natural vegetation categories (cerrado or forest) from the 1985 map were maintained. Hence, three classes were defined as forest, cerrado, and water areas.

LUC – 1960

The LUC for 1960 was created based on the previous described maps (T0 and 1985) and the mapping products of Dias *et al.*, 2016 (available at www.biosfera.dea.ufv.br/en-US/bancos). Dias *et al.*, 2016 made the first effort of a spatialized database of agriculture areas in Brazil between 1940 and 2012 that includes the percentage, per pixel, of croplands and grasslands. The reconstruction was based on satellite images and census of agriculture data obtained by municipality. Dias et al. (2016) provide the cropland and grassland areas estimates with an annual temporal resolution and 1 km of spatial resolution. To reconstructed LUC 1960, this work followed the steps described below:

I. The estimates provided by Dias *et al.* (2016) were used to define areas of cropland and grassland. Areas that characterize cerrado and forest are the same as in LUC T0. Urban areas, that represent less than 1% of the UPRB, are the same ones from the LUC 1985 map as it was assumed that urban categories maintained their areas between 1960 and 1985. The map from 1960 describing urban areas is not available on a large scale, existing only for a few municipalities, which is not appropriate to use in this study. Therefore, the conversion from cerrado and forest to urban areas were not evaluated from 1960 to 1985.

II. The map from T0 (RADAMBRASIL project), 1960 Dias *et al.* (2016), and 1985 Rudke (2018) with a spatial resolution of approximately 500 meters, 1 km, and 30 meters, respectively, were resampled to 90 meters by applying the bilinear interpolation technique (Hilker *et al.*, 2014).

III. Pixels with estimates of cropland and grassland lower than 15% were defined as natural vegetation areas. These areas followed the forest or cerrado categories from the T0 map.

IV. To pixels with estimates of cropland and grassland higher than 15% was assigned one of the two categories according to the highest percentage.

V. Pixels classifieds as urban areas, water, forest and cerrado from the 1985 LUC map were maintained in the 1960 LUC map. Areas of natural vegetation in 1985 are assumed to have been always natural and not a regeneration.

VI. The level of agreement of the proposed reconstruction methodology was evaluated. The aforementioned steps were applied to estimate the land use and cover of the 1985 map classified by Rudke (2018). Based on a Global Accuracy teste, the 1985´s reconstruction map presented a 72% similarity.

2.4.2.2 Model set up

The simulations for the three LUC were built with the same configuration described in section 2.3 (Hydrological modelling of the UPRB) that includes the parameterization and best-fit calibration parameters. As a result, the model generated 24,839 (LUC T0), 34,029 (LUC 1960) and 50,272 (LUC 1985) HRUs.

2.4.2.3 Construction of scenarios

Specific scenarios of discharge were created to assess and quantify the distinct impacts of 1960 to 1985 LUCC and of climate shift on the Paraná River annual discharge. They are summarized in Table 4 and described in the following.

Five discharge scenarios were created (A to E) based on four discharge simulations using different LUCs and precipitation periods before and after the climate shift (D1 to D4). Scenario A assesses the relative change in the average annual median discharge of D3 relative to D1; Scenario B is the same but of D4 relative to D2; Scenario C, of D2 relative to D1; Scenario D, of D4 relative to D3; and Scenario E of D4 relative to D1.

Scenario A provides an indication of the impact on the annual discharge of LUCC between 1960 and 1985 during the precipitation period 1961 – 1973 (before the climate shift) by comparing discharge simulations for 1961 to 1973 generated using LUC 1960 (D1) and LUC 1985 (D3). Scenario B is similar, but for the period 1978 to 1990 (after the climate shift).

Scenario C assesses the effect on the annual discharge of the changes in precipitation before (D1) and after (D2) the climate shift by considering a constant LUC 1960 in the simulations. Scenario D is similar but uses LUC 1985 on the simulations.

Finally, Scenario E estimates the effect of both LUCC and climate shift by comparing discharge simulations from periods before the climate shift and LUC 1960 (D1) and after the climate shift with LUC 1985 (D4).

In addition, five discharge scenarios (I to V) were constructed to assess the impact of LUCC from pristine time T0 to LUC 1985. They are similar to the previously described scenarios but considering T0 instead of LUC 1960 in the simulations (Table 5).

Table 4. Overview of the defined discharge series for the construction of the scenarios A to E.

Discharge	Description
D1	Discharge values between 1961 and 1973 from simulation with LUC 1960
D2	Discharge values between 1978 and 1990 from simulation with LUC 1960
D3	Discharge values between 1961 and 1973 from simulation with LUC 1985
D4	Discharge values between 1978 and 1990 from simulation with LUC 1985
Scenarios	**Description**
Scenario A	D3 minus D1
Scenario B	D4 minus D2
Scenario C	D2 minus D1
Scenario D	D4 minus D3
Scenario E	D4 minus D1

Table 5. Overview of the defined discharge series for the construction of the scenarios I to V.

Discharge	Description
D1’	Discharge values between 1961 and 1973 from simulation with LUC T0
D2’	Discharge values between 1978 and 1990 from simulation with LUC T0
D3’	Discharge values between 1961 and 1973 from simulation with LUC 1985
D4’	Discharge values between 1978 and 1990 from simulation with LUC 1985
Scenarios	**Description**
Scenario I	D3’ minus D1’
Scenario II	D4’ minus D2’
Scenario III	D2’ minus D1’
Scenario IV	D4’ minus D3’
Scenario V	D4’ minus D1’

2.4.2.4 Analysis of the effects of LUCC and Climate shift

For the analysis of the discharge resulting from the scenarios, ten outlets within UPRB were selected and included the largest rivers of the UPRB or those where the upstream subbasins had expressive replacement of natural vegetation (forest or cerrado) by cropland or grassland. The location of the selected outlets is shown in Figure 7. Four outlets of Paraná river were evaluated: Upper Paraná (4) after the confluence of Lower Tietê (3); Middle Paraná (6), before the confluence of Ivinhema (7), Lower Paraná (8), and Lower Paraná (10), the river mouth of the UPRB.

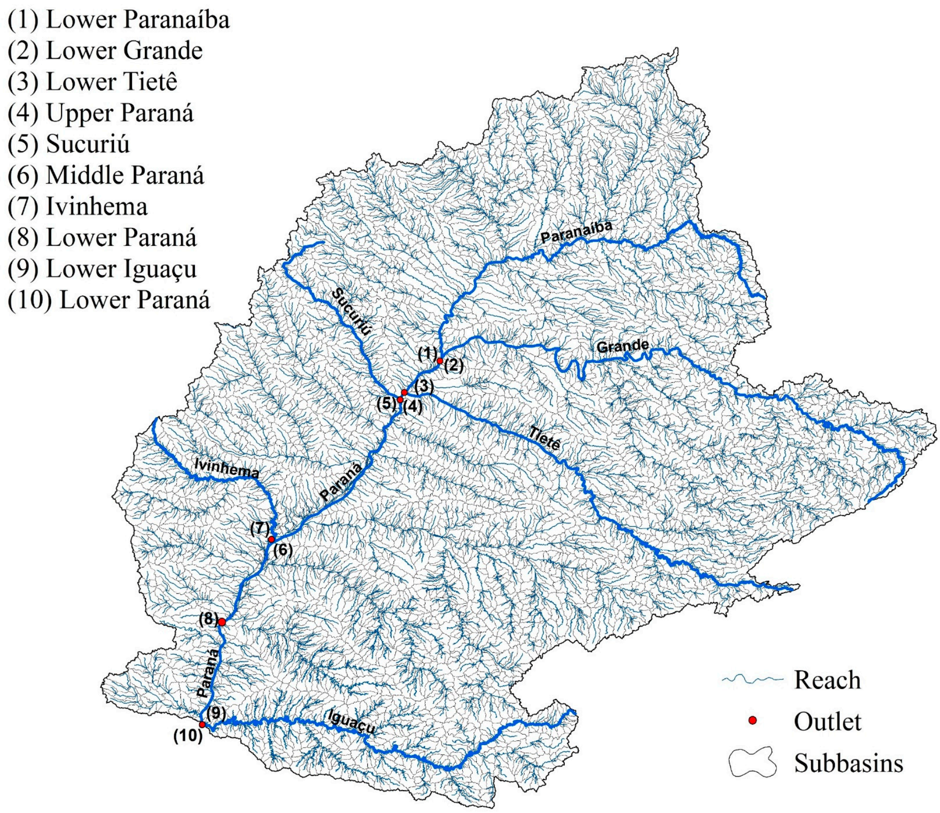

Figure 7. Location of the outlets selected with their respective number, and subbasins discretization.

3 Results and Discussion

This chapter combines the results obtained from the statistical analysis used to detect the trends of precipitation, hydrological modelling of the UPRB, and the results from the numerical scenarios. The main findings are presented. For further details, the reader is referred to the appended papers I to IV.

3.1 Analysis of the precipitation trends

In the following sections, the results of the trends detected by MK test are discussed as the division shown in Figure 2 into six subbasins: I – Paranaíba, II – Grande, III – Tietê, IV – Paraná, V – Paranapanema and VI – Iguaçu.

3.1.1 Annual and seasonal precipitation

Figure 8 shows the spatial distribution of trends of annual and seasonal precipitation totals between 1977 and 2016. The following significant trends (at the 95% confidence level) were found:

- **Annual:** 36 stations presented significant negative trends, being mostly located at Grande (20) and Paranaíba (8) subbasins. 34 presented significant positive trends, concentrated in parts of the Paranapanema (12), Iguaçu (11) and Paraná (9) subbasins.

- **Summer:** negative trends are observed mostly in the Paranaíba (9) and Grande (4) subbasins. Positive trends are concentrated in the southeast of the Paraná (12), Iguaçu (5) and Paranapanema (4) subbasins.

- **Autumn:** all the significant trends were negative, and they were mainly located in the central portion and northeastern region of the UPRB.

- **Winter:** few stations presented significant trends, with a clear north-south separation. Negative trends predominated in the north (9) and positive in the south (4) of the basin.

- **Spring:** Statistically significant negative trends predominated in the northeastern region of the UPRB, with 16 stations in the Grande subbasin.

The spatial distribution of trends of annual and seasonal total precipitation shows that significant negative trends are mostly located in the northern part at Paranaíba and Grande subbasins. A decreasing amount of precipitation in those regions may have a significant impact on energy generation as these basins house 70 hydropower plants that, together, provide more than 17,000 MW of electricity (ANEEL, 2020). In contrast, the significant positive trends are concentrated in the southern part particularly in the Paranapanema and Iguaçu subbasins, notably in the summer season.

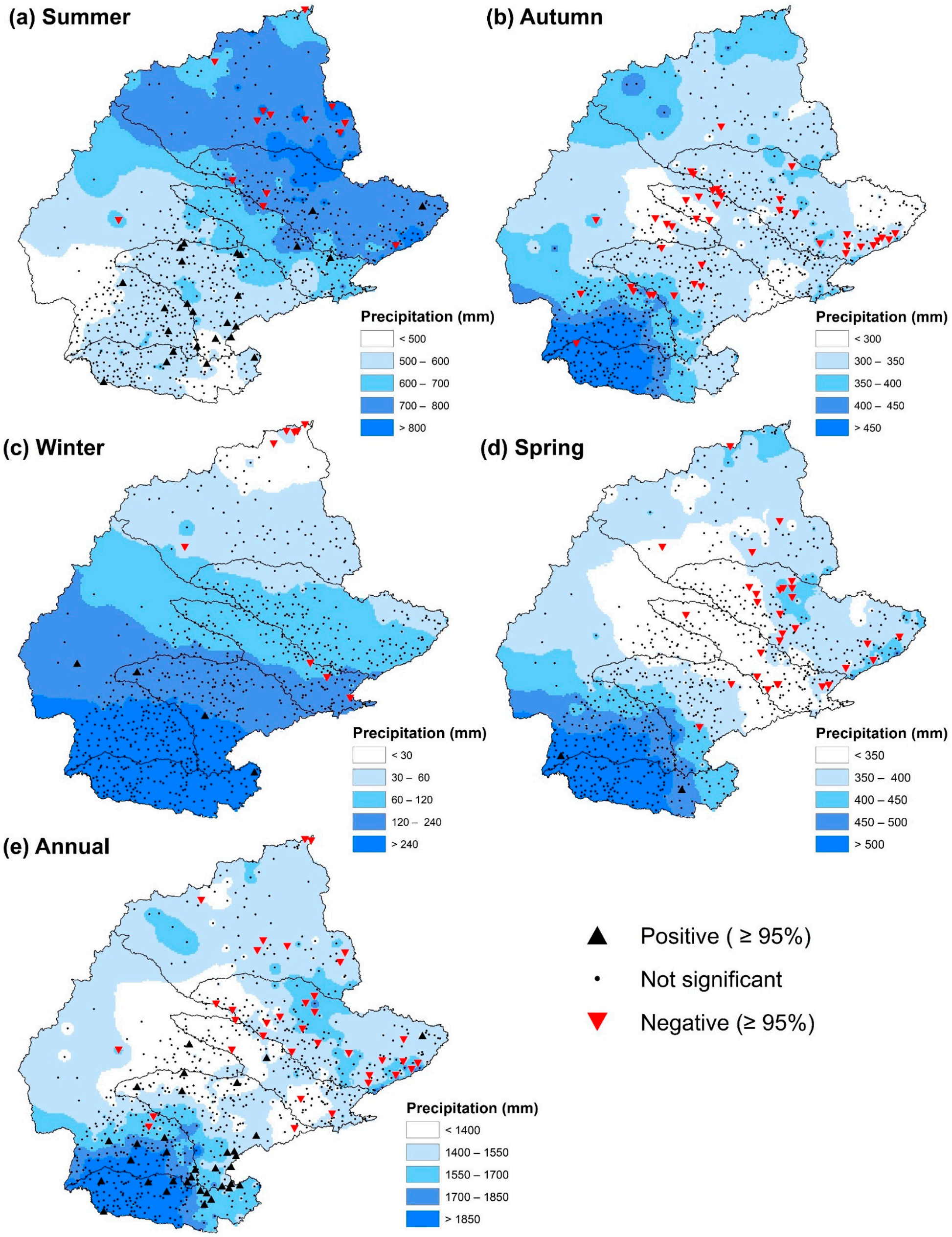

Figure 8. Spatial distribution of trends and interpolated values of annual and seasonal average precipitation totals in the UPRB over the period of 1977–2016 for (a) summer, (b) autumn, (c) winter, (d) spring, and (e) annual. The blue-shaded patterns are the annual and seasonal values, triangles show the significant trend (red is negative, and black is positive), and black circles indicate no significant trend.

From Abou Rafee *et al.* (2020).

3.1.2 Extreme precipitation events

Figure 9 illustrates the spatial distribution of trends of four extreme precipitation indices detected between 1977 and 2016. The following significant trends (at the 95% confidence level) were found:

- **Annual greatest 5-day total precipitation (px5d):** 20 stations presented positive significant trends observed mostly on the central portion of the basin. 9 of these stations are located at the lower Paranapanema subbasin, where extreme precipitation events were witnessed and caused considerable damages (e.g. Camilloni and Barros 2000). On the other hand, 14 stations with negative trends were detected mostly located in the northern and northeastern regions of the UPRB.

- **Annual mean precipitation per rainy day $\left(\geq \mathbf{1}\ \boldsymbol{mm\ day^{-1}}\right)$ (pint):** 263 stations were identified with a significant trend. 87% of these stations presented positive trends and are mostly located at the Paraná subbasin, with 70 stations, followed by the Paranapanema (54) and Iguaçu (48) subbasins. This result is in accordance with previous studies (Zandonadi *et al.*, 2016) and indicates that most of the areas of the basin are lengthening the wet season.

- **Annual maximum number of consecutive dry days $(< \mathbf{1}\ \boldsymbol{mm\ day^{-1}})$ (pxcdd):** 41 stations showed a significant trend, of which 36 are positive and 5, negative. Most of these (15) located in the northern region of the UPRB, particularly in the northern Paranaíba subbasin, which is the region that presents a high number of dry days (> 90). This might have a significant impact as the subbasin is home of the Corumbá IV reservoir, which is responsible for the water supply of 1.3 million inhabitants.

- **Annual number of days with precipitation $(> \mathbf{50}\ \boldsymbol{mm\ day^{-1}})$ (pn50):** 85 stations showed a significant trend, of which 60 are positive and 25, negative. Positive trends are mostly located on the south and negative ones on the northeast of UPRB. The positive trends could be associated with the increasing trends in strength and frequency of SALLJ over southern Brazil as reported by Montini *et al.* (2019).

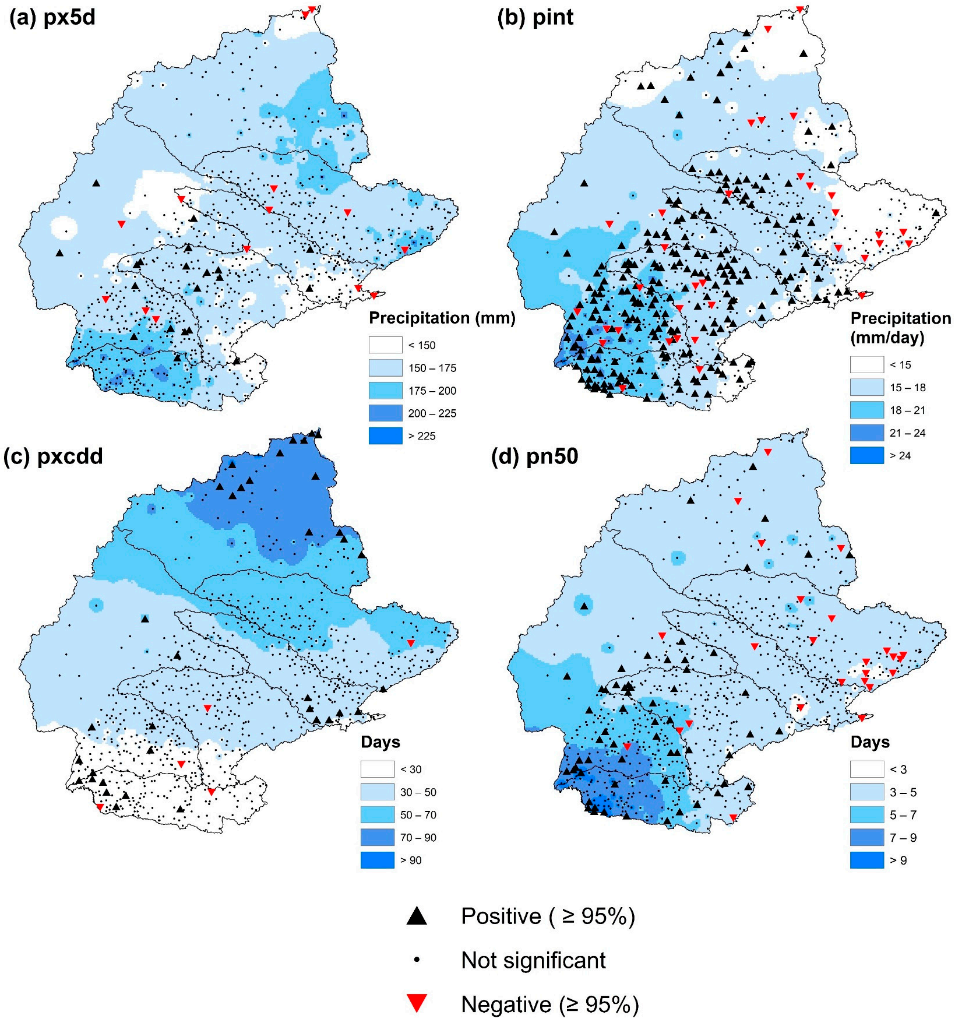

Figure 9. Spatial distribution of trends and interpolated values of annual average extreme precipitation indices in the UPRB over the period of 1977–2016 for (a) px5d, (b) pint, (c) pxcdd, and (d) pn50. The blue-shaded patterns are average extreme precipitation indices values, triangles show the significant trend (red is negative, and black is positive), and black circles indicate no significant trend.

From Abou Rafee *et al.* (2020).

3.2 SWAT model performance

In this section, the main results of calibration and validation for the main discharge rivers of the UPRB are presented. Furthermore, the values of LAI considering all the HRUs are illustrated. For more details, the reader is encouraged to refer the Papers II and III as well as their supplementary materials.

3.2.1 River discharge

As shown in Figure 10, the simulated results were consistent with the observed monthly discharge at the main rivers of the UPRB. According to the performance rating proposed by Moriasi *et al.* (2007) and Thiemig *et al.* (2013) Thiemig et al. (2013), the simulations ranged from satisfactory to very good in the statistical indices presented in Table 6. During the calibration period (1984 – 2004), PBIAS ranged from -0.2 to 6.4, R^2 from 0.71 to 0.88, NSE from 0.7 to 0.8, KGE from 0.7 to 0.9, and RSR from 0.44 to 0.55. For the validation period (2005 – 2015), the simulations reached index values up to 0.7 for PBIAS and 0.92 for R^2 (at Grande river), and, 0.84 for NSE, 0.88 for KGE, and 0.4 for RSR (at Paranaíba river).

3.2.2 Leaf Area Index

The average monthly simulated LAI values considering all the HRUs for the whole basin are presented in Figure 11. SWAT vegetation parameters were manually calibrated to adjust the magnitude and shape of LAI in accordance with the observations (Bucci *et al.*, 2008, Hoffmann *et al.*, 2005, Negrón Juárez *et al.*, 2009). The estimated values of LAI ranged between 2.5 and 5.5 $m^2\ m^{-2}$ for forest, 0.7 and 2.5 $m^2\ m^{-2}$ for cerrado, and 0.5 and 2.0 $m^2\ m^{-2}$ for grassland. As shown in Figure 11, LAI varies seasonally with the highest values within the wet season (October – March), and the lowest values in the dry season (April – September) due to the dormancy period. LAI values from the current study are comparable to those simulated by Dos Santos *et al.* (2018), who used SWAT to evaluate the impacts of LUCC on hydrology in the Iriri River basin in the Brazilian Amazon. Their results showed LAIs with annual averages of 4.02, 1.25, and 1.09 $m^2\ m^{-2}$ (versus 3.53, 1.49, and 1.23 $m^2\ m^{-2}$ in this study) for the forest, cerrado, and grassland, respectively.

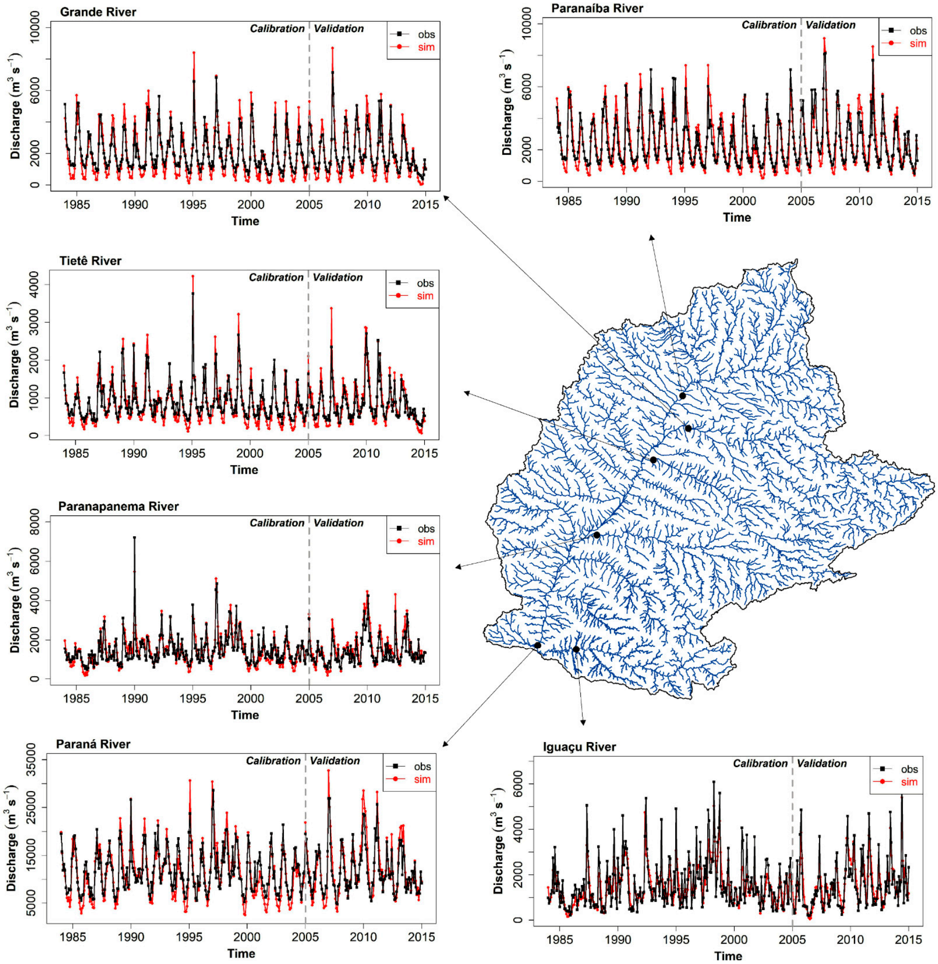

Figure 10. Comparison between the observed and simulated monthly discharge at the main rivers of the UPRB.

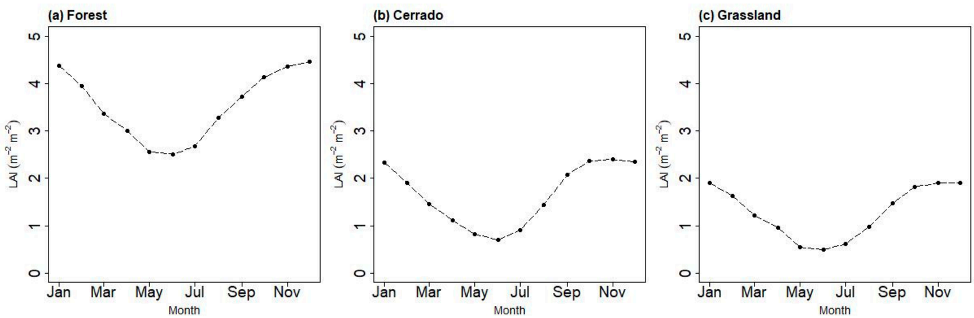

Figure 11. Average monthly simulated LAI values considering all HRUs from LUC 2015 scenario for Forest (a), Cerrado (b), and Grassland (c).

Table 6. SWAT model performance for the main rivers of the UPRB.

Outlet	Index	Calibration (1984 - 2004)	Validation (2005 - 2015)	Whole Period
Paranaíba	PBIAS	0.1	-4.5	-1.5
	R^2	0.82	0.87	0.84
	NSE	0.76	0.84	0.79
	KGE	0.81	0.88	0.84
	RSR	0.49	0.40	0.45
Grande	PBIAS	6.4	0.7	4.5
	R^2	0.88	0.92	0.89
	NSE	0.75	0.82	0.78
	KGE	0.71	0.73	0.72
	RSR	0.5	0.42	0.47
Tietê	PBIAS	5.7	-3.9	2.6
	R^2	0.87	0.86	0.86
	NSE	0.78	0.74	0.77
	KGE	0.78	0.72	0.76
	RSR	0.47	0.51	0.48
Paranapanema	PBIAS	-0.2	-12.9	-4.6
	R^2	0.82	0.88	0.83
	NSE	0.80	0.74	0.78
	KGE	0.90	0.75	0.85
	RSR	0.44	0.51	0.46
Iguaçu	PBIAS	5.5	-0.8	3.3
	R^2	0.71	0.78	0.74
	NSE	0.70	0.77	0.72
	KGE	0.70	0.75	0.72
	RSR	0.55	0.48	0.52
Paraná	PBIAS	3.6	-6.2	0.2
	R^2	0.84	0.87	0.84
	NSE	0.75	0.75	0.75
	KGE	0.78	0.75	0.76
	RSR	0.50	0.50	0.50

3.3 Analysis of LUC 1985 versus LUC 2015

3.3.1 Detection of LUCC transitions

The total area of the main transitions of LUCC between 1985 and 2015 at the major subbasin level are shown in Figure 12. The largest areas of LUCC were the conversion from grassland to cropland occurred within the Brilhante/Ivinhema (27) and Lower Tietê (16) subbasins, which reached up to 8,490 and 9,250 km^2, respectively. Besides, in the Carapá/Guaçu/Lower Paraná (34) subbasin, 6,640 km^2 of forests were replaced by cropland areas. Most of these areas were replaced mainly by sugarcane cultivation due to the high demand for bioenergy in the form of ethanol and raw material for the thermoelectric power plants (Adami *et al.*, 2012, Rudorff *et al.*, 2010). Also, this growth is largely caused by the development of agricultural mechanization, climate conditions, population growth, and economic factors (Mueller & Mueller, 2016). Particularly, in the southern part of the basin, the main reason for the expansion of cropland was the construction of the Itaipu hydroelectric power plant (1974 – 1985) at the border between Brazil, Argentina, and Paraguay. This construction made an important contribution to rapid population growth in the region (Baer & Birch, 1984). It is also worth mentioning that the increase of areas of cropland in the basin happens over areas that were previously covered with cerrado. Deforestation of cerrado contributed to an increase of up to 6,550 km^2 in cropland areas in the Corumbá (1) and Upper Paranaíba (2) subbasins. Still, cerrado reductions also had a significant contribution to the grassland expansion. For example, about 6,670 km^2 of cerrado were deforested replaced by grassland in the Anhanduí/Pardo (22) subbasin.

The central-western and northern parts of the basin were the ones that most witnessed afforestation or reforestation in the last recent decades. For example, the transition from cerrado to forest in the Corumbá (1) and Anhanduí/Pardo (22) subbasins contributed to a forest cover increase of up to 3,070 and 3,040 km^2, respectively. The increase in forests is mainly related to the transitions of the LUC classes of cerrado, grassland, and cropland to Eucalyptus plantations. According to the Brazilian Association of Forest Plantation Producers, the growth of Eucalyptus in Brazil has been mainly driven by the profit growth generated that is up to six times greater than the one of livestock production. Besides economic issues, Gonçalves *et al.* (2008) pointed out that the increase of Eucalyptus plantation is due to the investments in research and technology in the last decades, which improved seed or clonal plantations.

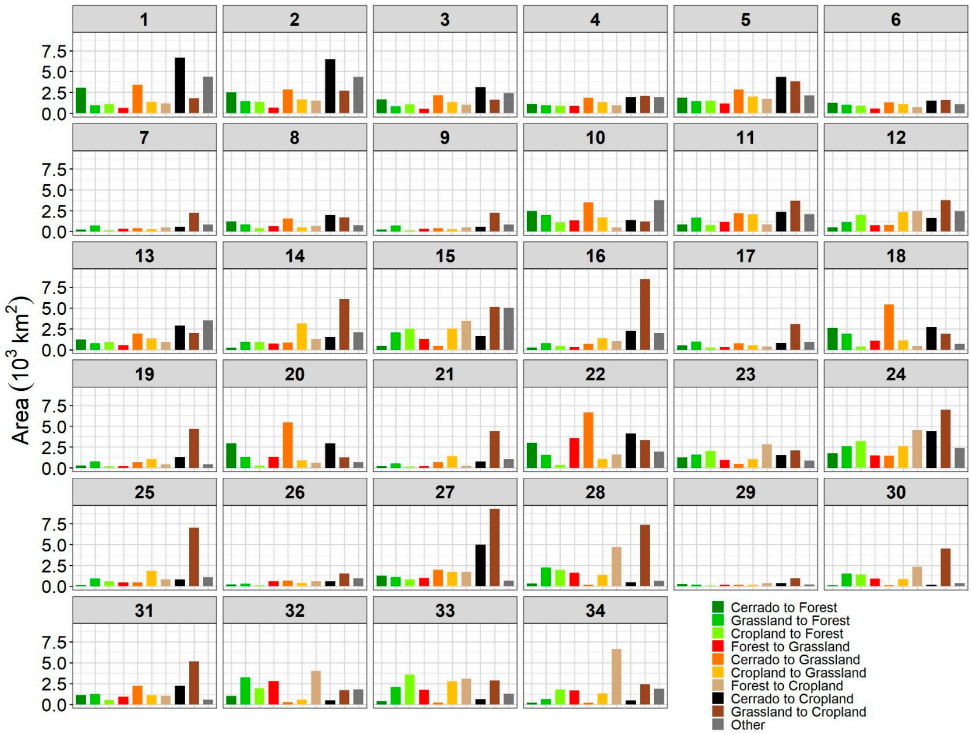

Figure 12. Area (10^3 km^2) of the main transitions of LUCC between 1985 and 2015 at the major subbasins of UPRB. **1.** Corumbá; **2.** Upper Paranaíba; **3**. Araguari; **4.** Meia Ponte-Middle Paranaíba; **5.** Dos Bois; **6.** Tijuco; **7.** Middle Paranaíba; **8.** Claro; 9. Verde-Corrente-Aporé or Do Peixe-Lower Paranaíba; **10.** Upper Grande; **11.** Sapucaí; **12.** Pardo; **13.** Middle Grande; **14.** Lower Grande; **15.** Upper Tietê; **16**. Lower Tietê; **17.** São José dos Dourados-Upper Paraná; **18.** Sucuriú; **19.** Aguapei or Feio; **20.** Verde; **21.** Do Peixei-Middle Paraná; **22.** Anhanduí-Pardo; **23.** Tibagi; **24.** Upper Paranapanema; **25.** Lower Paranapanema; **26.** Middle Paraná; **27.** Brilhante-Ivinhema; **28.** Ivaí; **29.** Middle Paraná; **30.** Piquiri; **31.** Iguatemi-Middle Paraná; **32.** Upper Iguaçu; **33.** Lower Iguaçu; **34.** Carapá-Guaçu-Lower Paraná.

3.3.2 Effects of LUCC on hydrology

The two simulated scenarios for the LUC from 1985 and 2015 with unchanged climatic conductions were compared. The effects of LUCC on hydrologic components within the basin are illustrated in the spatial distribution of changes in surface runoff, actual evapotranspiration, and soil moisture (Figure 13). These changes were calculated considering the long-term means (1984 – 2015) from the difference between LUC2015 and LUC1985 simulated hydrologic variables for annual (October – September), wet (October – March), and dry (April – September) season values. Also, to address the LUCC impacts for interannual variation of climate, box plots of annual and seasonal from 32 years (1984 – 2015) for hydrological variables were calculated (see Figure 14), considering the means values of simulated hydrological variables at the major subbasin level (as shown in Figure 6).

3.3.2.1 Surface runoff, actual evapotranspiration, and soil moisture

Overall, the LUCC caused an increase in the annual and wet season surface runoff, while a decrease in the dry period (Figure 13 and Figure 14). The interannual values show that the increases at the major subbasins level reach up to 31.8 and 25.3 mm in the annual and wet season runoff, respectively. In contrast, the decrease overtakes 5.6 mm in the dry season. The effects are remarkable at the Corumbá (1), Upper Paranaíba (2), Corrente, Aporé or do Peixe (9), and Carapá-Guaçu-Lower Paraná (34) subbasins. In these regions, a major cause for the increase in surface runoff is the substantial removal of the cerrado and forest vegetation, replaced mainly to cropland and grassland (see Figure 12). In addition, it was observed a significant increase in the Lower Tietê (16), Brilhante-Ivinhema (27), Piquiri (30) watersheds. However, in these regions, an expressive reduction of cerrado and grassland areas replaced by cropland was observed.

In addition, it should be noted in the spatial distribution (Figure 13) that small catchments presented a decrease in surface runoff during the wet season. This could be attributed to the increase in forest areas due to the afforestation (e.g. cerrado to forest) and reforestation (e.g. grassland to forest).

In SWAT, the surface runoff is estimated by the Curve Number (CN) method (USDA Soil Conservation Service, 1972). CN varies spatially according to LUC, soil type, and slope. It can be easily interpreted by the order of higher values: Urban>Cropland>Grassland>Cerrado>Forest. Consequently, the increase or decrease in the generated runoff during the period could be explained by the major conversions of LUC in the basin such as from cerrado to cropland, or from grassland to cropland. Also, CN has temporal variation due to changes in soil moisture. During the dry season, a possible explanation for the decreasing amounts of surface runoff is due to the reduction in the water content storage. Li *et al.* (2015) who applied the SWAT model also observed runoff decrease due reduction in soil water storage during dry season over deforestation areas in the south-eastern Fujian Province of China.

In contrast to surface runoff, a decrease in the actual evapotranspiration mainly in the annual and wet season was observed. A decrease greater than 200 mm mostly in central-western (e.g. Anhanduí-Pardo (22)) and southern parts (e.g. Carapá-Guaçu-Lower Paraná (34)) of the basin (Figure 13) was observed. For instance, in these watersheds it was observed a median decrease considering the mean values discretization up to 110, 87, and 21 mm in the annual, wet and dry season, respectively (Figure 14). Similar to surface runoff, this is likely because of the natural vegetation suppression that were replaced by cropland areas. The reduction in the actual evapotranspiration values is explained by the shallower roots of cropland or grassland compared to natural vegetation (forest or cerrado), which leads to less access to deep soil moisture (Nepstad *et al.*, 1994, Oliveira *et al.*, 2005). Also, the mean LAI values are smaller which consequently decreases the transpiration.

It is important to highlight that even in the dry season, the spatial distribution (Figure 13) shows that in the Carapá-Guaçu-Lower Paraná (34) and Lower Iguaçu (33) subbasins there is a significant increase in the amounts of surface runoff and decrease in the actual evapotranspiration. Besides the influence of LUCC, the precipitation in this region in the dry period is much higher compared to the other parts of the basin (Abou Rafee *et al.*, 2020).

As shown in Figure 13, the impacts of LUCC on soil moisture storage ranged from an increase up to 400 mm to a decrease up to 100 mm within the major subbasin level. Similar to surface runoff, it was observed mainly an increase in the wet and annual values, and a decrease in the dry season. The higher values of soil moisture during the wet season are explained by the reduction of actual evapotranspiration. As mentioned previously, it occurred as a result of the removal of cerrado areas and the expansion of cropland in the basin.

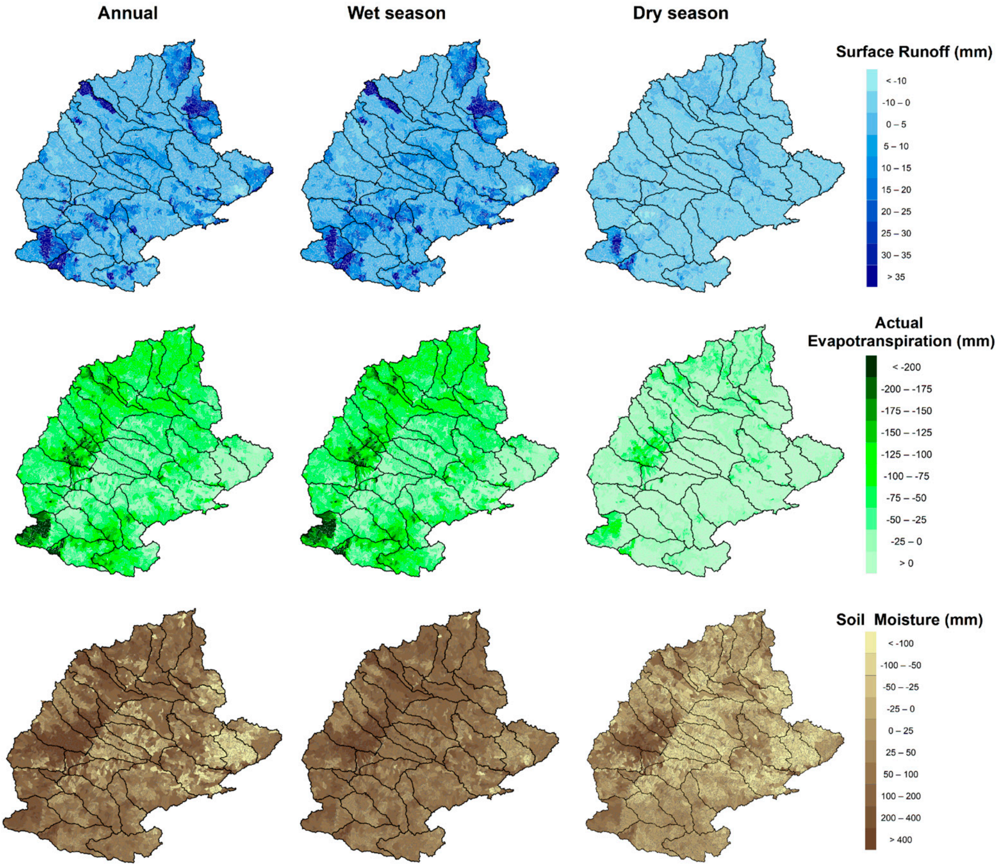

Figure 13. Spatial distribution of changes (mm) in surface runoff, actual evapotranspiration, and soil moisture considering the long-term means (1984 – 2015) for the annual, wet, and dry season values calculated from the difference between the simulated scenarios (LUC2015 minus LUC1985).

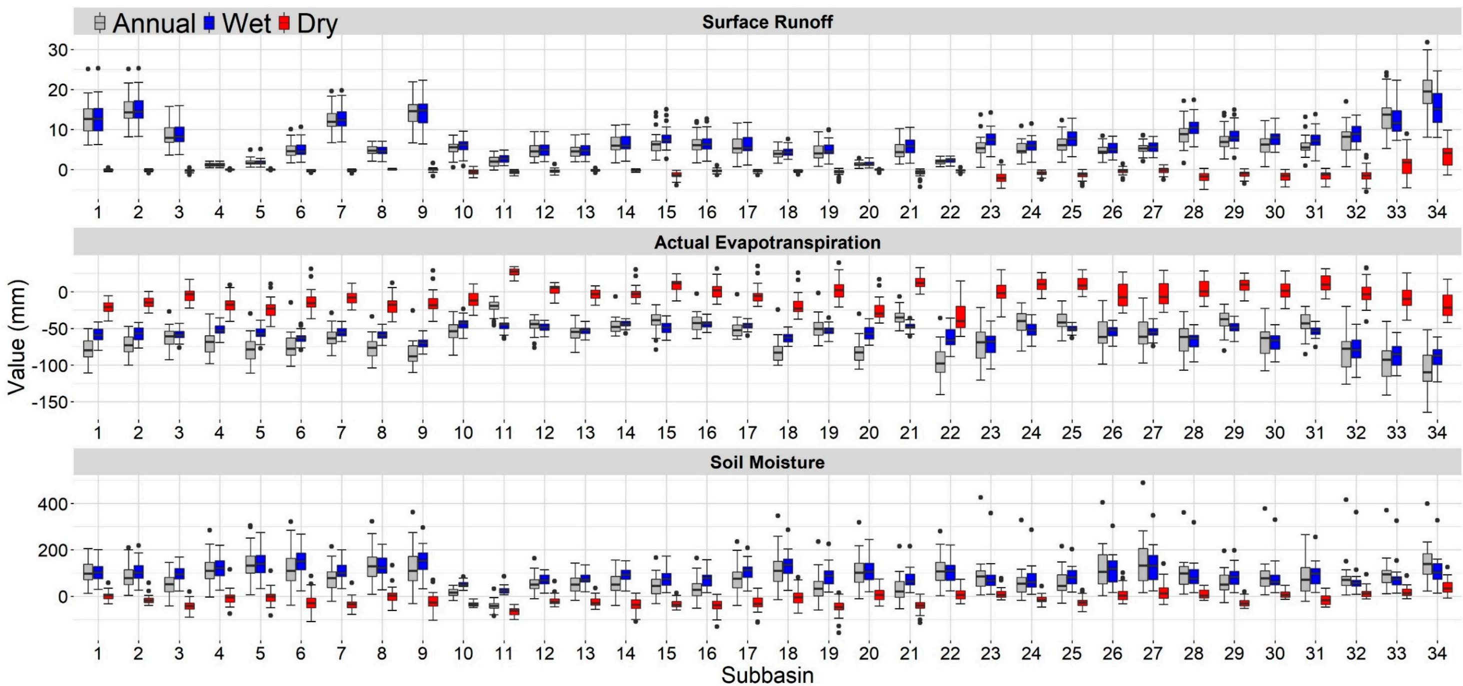

Figure 14. Box plots of surface runoff, actual evapotranspiration, and soil moisture for annual and seasonal (wet and dry) values from 32 years (1984 – 2015). There were calculated from the difference between the simulated scenarios (LUC2015 minus LUC1985) at major subbasin level. **1.** Corumbá; **2.** Upper Paranaíba; **3.** Araguari; **4.** Meia Ponte-Middle Paranaíba; **5.** Dos Bois; **6.** Tijuco; **7.** Middle Paranaíba; **8.** Claro; **9.** Verde-Corrente-Aporé or Do Peixe-Lower Paranaíba; **10.** Upper Grande; **11.** Sapucaí; **12.** Pardo; **13.** Middle Grande; **14.** Lower Grande; **15.** Upper Tietê; **16.** Lower Tietê; **17.** São José dos Dourados-Upper Paraná; **18.** Sucuriú; **19.** Aguapei or Feio; **20.** Verde**; 21.** Do Peixei-Middle Paraná; **22.** Anhanduí-Pardo; **23.** Tibagi; **24.** Upper Paranapanema; 25. Lower Paranapanema; 26. Middle Paraná; **27.** Brilhante-Ivinhema; **28.** Ivaí; **29.** Middle Paraná; **30.** Piquiri; **31.** Iguatemi-Middle Paraná; **32.** Upper Iguaçu; **33.** Lower Iguaçu; **34**. Carapá-Guaçu-Lower Paraná.

3.3.2.2 River discharge

The simulation results revealed that the LUCC between 1985 and 2015 had an expressive impact on discharge values. Overall, the LUCC implied an increase in the annual's and wet season's discharges at the main rivers of the UPRB. The major relative changes in discharge were observed at the Lower Tietê, Anhanduí, Ivinheima, and Guaçu rivers. For instance, an increase of more than 29% in annual mean values was found at the Guaçu river. All of these subbasins have in common a significant reduction in natural vegetation (forest or cerrado). On the other hand, a decrease was observed during the dry period, except for Anhandui and Guaçu rivers. A mean decrease of more than 4% was observed at the Lower Tietê, Lower Paranapanema, and Sucuriú rivers. This behavior decreases the effect of annual increased discharge in many rivers of the basin. For example, at the river mouth of the UPRB, over the Lower Paraná River, it was observed an increase in the annual discharge of only 1.13%, an increase of 4.25% in the wet, and a decrease of only 2.24% in the dry season (Figure 15).

Surface runoff is one of the major contributors to discharge. Thereby, the changes in annual and wet season discharge values are likely associated with the increase of generated runoff in the subbasins. The results presented here are consistent with other large-scale simulations. For instance, Costa *et al.* (2003) analyzed the effects of large-scale changes on the discharge of the Tocantins River, southeastern Amazonia. The authors observed an increase in the average annual long-term discharge due to the conversion of the natural vegetation to cropland and grassland.

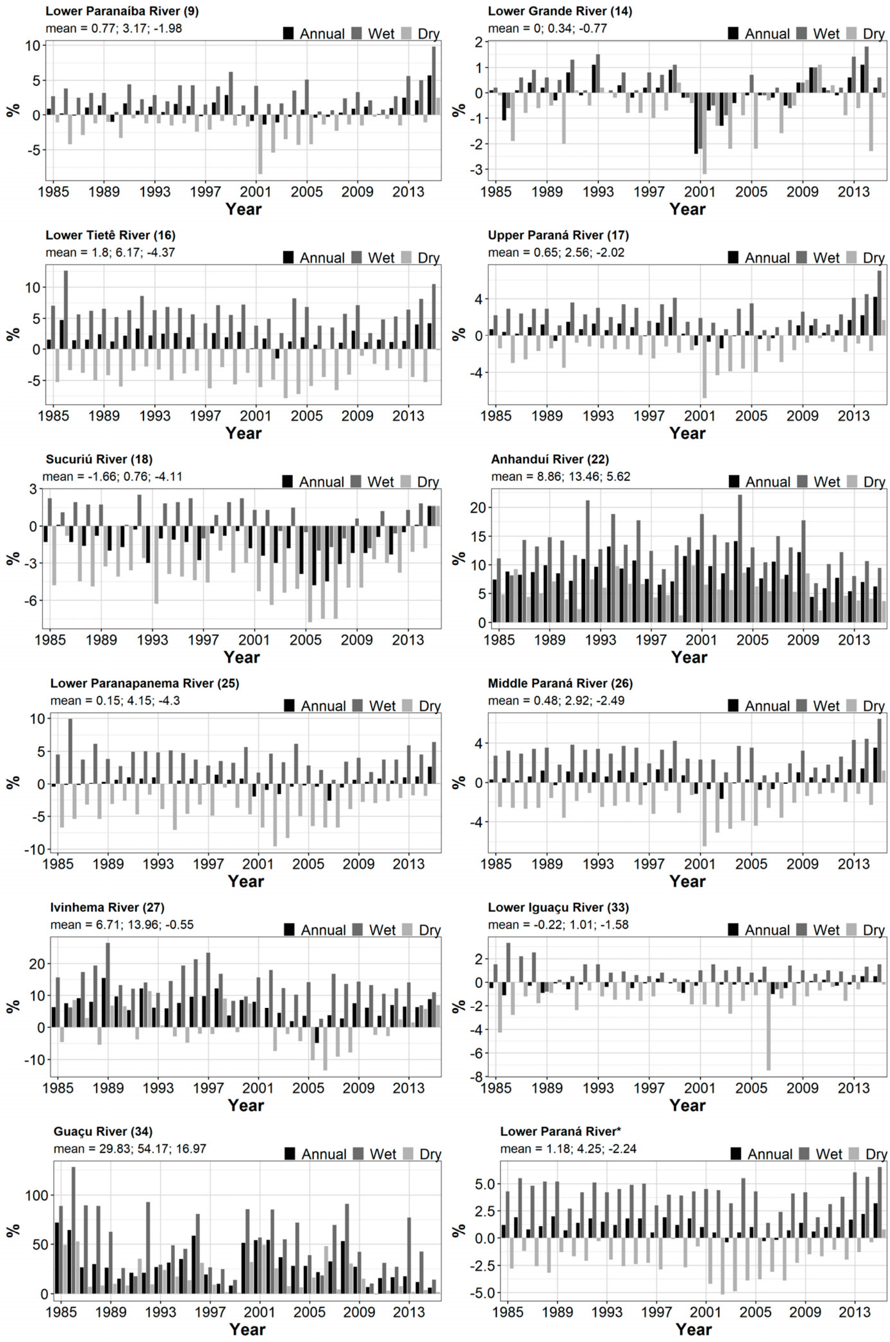

Figure 15. Temporal evolution of relative changes (%) in discharge for annual, wet and dry seasons under the scenarios for the year 2015 relative to 1985 at the main rivers of the UPRB. At the top left of

the plots are shown the mean values and the name of the rivers with the respective number of the subbasin. *The last graph represents the river mouth of the UPRB.

3.4 Analysis of LUCC versus Climate shift

3.4.1 LUC T0, 1960 and 1985

Figure 16 shows the generated LUC map from T0, 1960, and 1985. Overall, the east part of the basin has undergone the greatest suppression of the natural vegetation. Forested areas decreased from 57% of the total area of the basin in T0 to 35.9% in 1960, and to 17.6% in 1985. The area of cerrado decreased only 1.4% from T0 to the reconstruction for 1960, but it experienced an expressive reduction from 1960 to 1985 to almost half of the original area.

The original vegetation areas were replaced mainly by grassland and cropland, which represents, respectively, 9% and 12% of the area in 1960, and 27.7% and 31.1%, in 1985. In 1960, grassland and cropland areas are mostly located in the central-eastern part of the UPRB, close to the main socio-economical center of the basin, São Paulo State. For example, the Tietê subbasin has only a few fragments of its original LUC in 1960. As described in the methodology section, areas classified as water on LUC 1985 map were maintained in LUC T0 and LUC 1960, and represent 1.7% of the basin. Urban areas cover 0.9% of the UPRB in both 1985 and 1960 LUC. No urban areas are present at T0.

As noted in Figures 16a-c, the rate of LUCC from T0 to 1960 is much lower than from 1960 to 1985. This can be associated with the development of agri-business in Brazil that started in the early 1960s, which resulted in an extensive transformation of the ecosystems (Mueller & Mueller, 2016; Salazar *et al.*, 2015). Also, LUCC was driven by the exponential increase of the population in the early 1960s (IBGE, 2010).

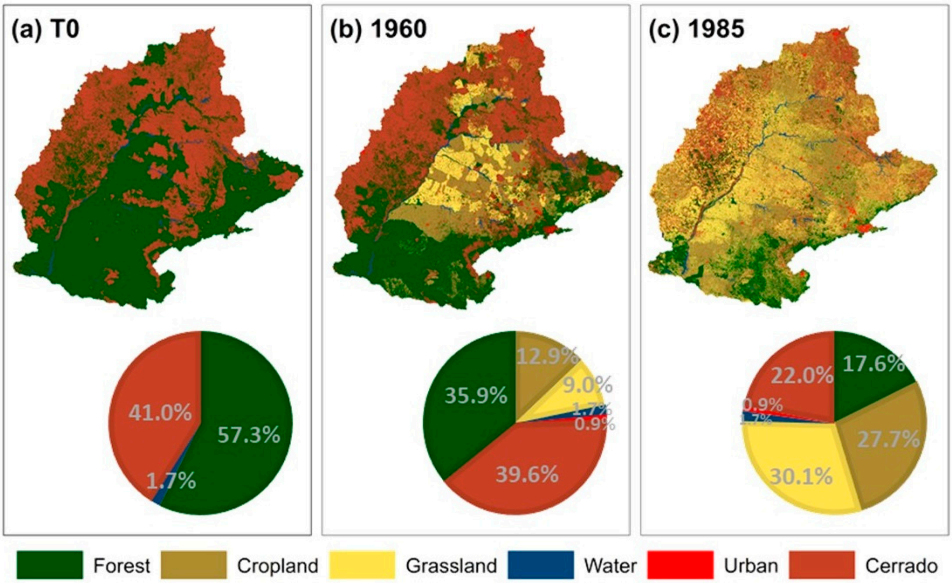

Figure 16. Land use and Cover (LUC) for (a) T0; 1960 (b) and 1985 (c).

3.4.2 Precipitation change

Figure 17 shows the relative changes in the average annual median precipitation under the period 1978 – 1990 relative to 1961 – 1973. The data were interpolated using the IDW method at the grid resolution of 0.05 degrees. Overall, the changes in precipitation were mostly positive and occurred mainly in the southern parts of the basin. Only specific areas in the north-eastern part of the UPRB presented a decrease in precipitation.

In the northern part of the basin, the increased precipitation values are mostly ranging between 0 – 10% and some areas up to 15%. This increase could be associated with the significant changes in the SAMS in early the 1970s as reported by Carvalho *et al.* (2011). According to the authors, the mean duration of SAMS wet period increased from 170 days (1948–1972) to 195 days (1972–1982).

In the southern region of the UPRB, the annual median precipitation increased more than 20%. Our results are supported by the ones from Liebmann *et al.* (2004) that observed increase of precipitation in this region after the observed climate shift, observing increasing when comparing the 1948 – 1975 period to 1976 – 1999, i.e., before and after the climate shift. The precipitation increase in this southern region is related to the fact that this area is more affected by the low frequency oscillations such as ENSO and PDO if compared to other parts of the basin (e.g. Cavalcanti *et al.*, 2015, Grimm *et al.*, 2000, da Silva *et al.*, 2011). Grimm *et al.* (1998) connects ENSO and PDO to the strengthened of the upper-tropospheric subtropical jet, that intensifies the MCS inducing more precipitation over the region.

It is important to recognize that many rain gauge stations have a high percentage of missing data, especially before the climate shift period, which may affect the results of the interpolation method. However, the basin has 629 stations with less than 5% missing data that are mainly located in the central-east and south-east of the basin, areas where the increase in precipitation before and after the climate shift can be seen (Figure 17).

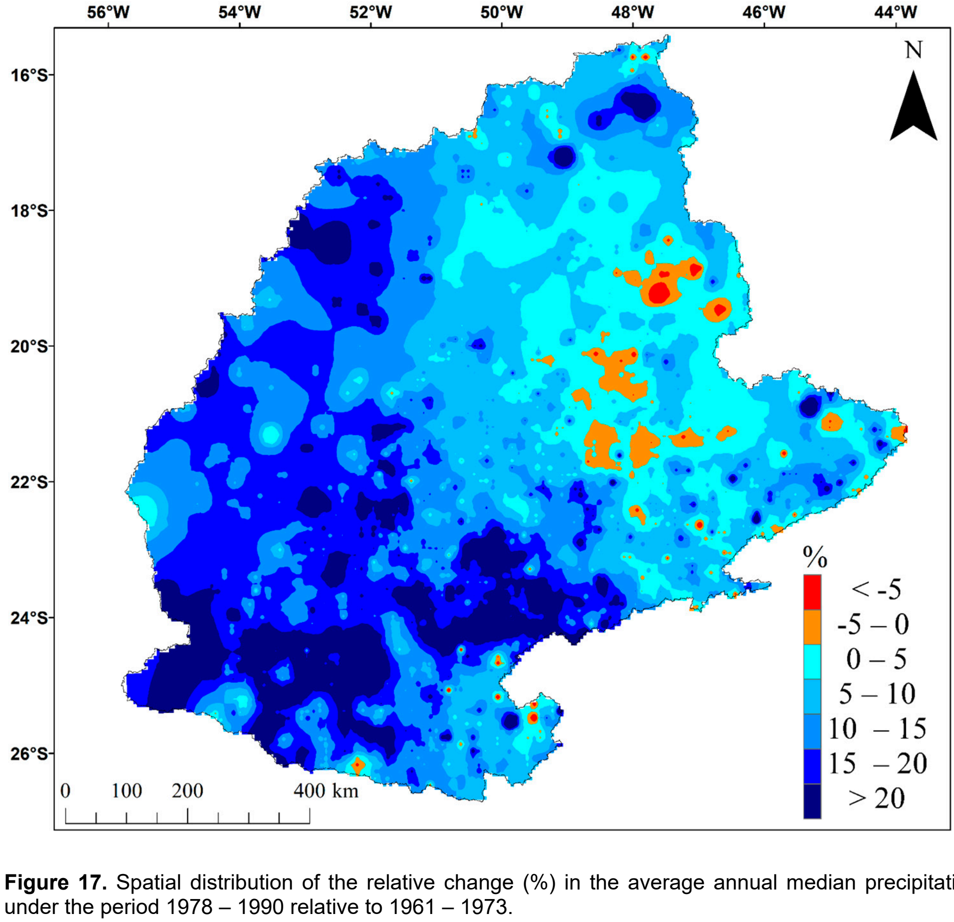

Figure 17. Spatial distribution of the relative change (%) in the average annual median precipitation under the period 1978 – 1990 relative to 1961 – 1973.

3.4.3 LUCC 1960 – 1985 versus Climate shift

Figure 18 illustrates the relative changes (%) in the average annual median discharge at ten UPRB sites following the A to E scenarios in Table 4. Overall, all scenarios and runs resulted in increased discharge. Also, the scenarios related to the climate shift (C and D) had higher increases compared to only LUCC scenarios (A and B).

Considering the precipitation from 1961 – 1973, scenario A showed that the LUCC between 1960 and 1985 lead to an increase in annual discharge from 4% up to 16.7% (at Ivinhema river), except for the Lower Grande river where the increase was of 1.8%. Scenario B, which considers the precipitation during the period 1978 – 1990, the LUCC from 1960 to 1985 lead to increased discharge of about 11% and 18% at the Lower Iguaçu and Ivinhema rivers, respectively. Both rivers had significant LUCC in their upstream subbasins as shown in Figure 16.

Scenarios C and D show the impacts in annual discharge due to the changes in precipitation before and after the climate shift (1961 – 1973 and 1978 – 1990) considering the LUC from 1960 and from 1985, respectively. Results show that the southern parts of the basin presented the highest increases in discharge. For instance, both scenarios showed that the Lower Iguaçu and Lower Paraná rivers had an increase of more than 30% in the average annual median discharge when comparing the 1961 – 1973 and 1978 – 1990 periods.

Scenario E assesses the joint effect of LUCC and climate shift on discharge. The highest increases in discharge are observed at the Ivinhema and Lower Iguaçu rivers outlets (Figure 18) with about 67% and 52%, respectively. This scenario clarifies that the discharge from the Paraná river increased from one period to the other and that this increase amplifies from upstream to downstream due to the confluence of the largest rivers. The sites Upper, Middle and, Lower Paraná (Figure 18, river mouth of the UPRB) rivers presented a discharge increase of about 14%, 15%, and 38%, respectively.

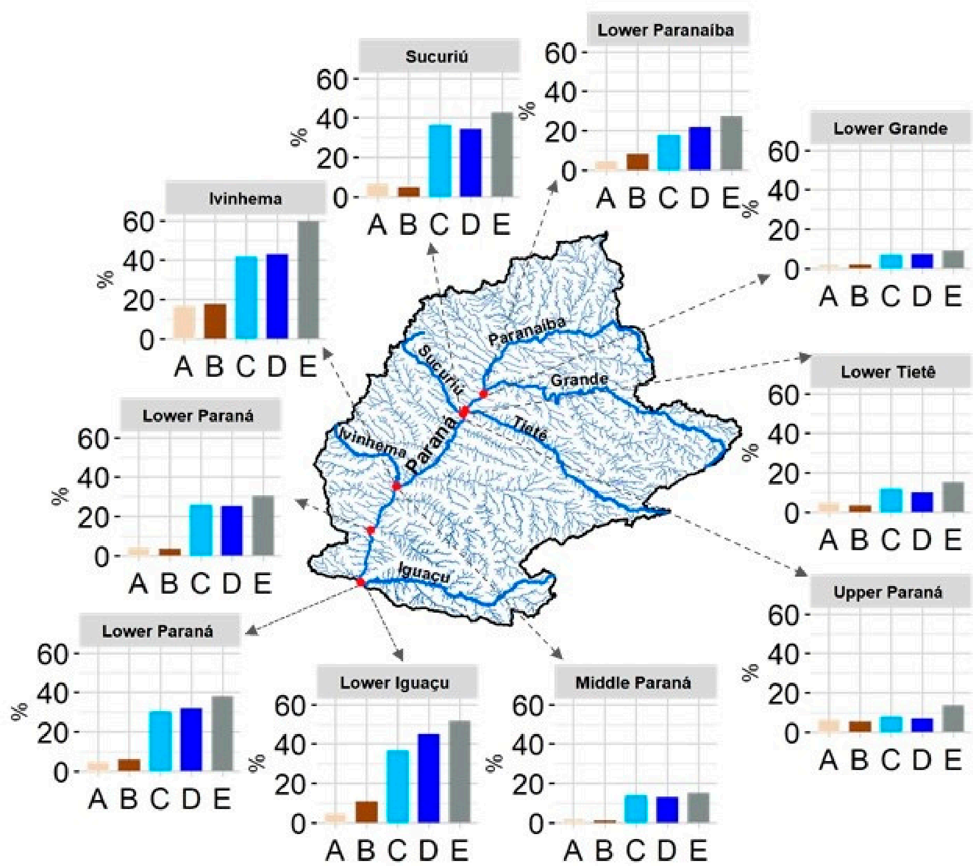

Figure 18. Relative changes (%) in the average annual median discharge at the largest river of the UPRB in scenario A to E. The scenarios are defined in Table 4.

3.4.4 LUCC T0 – 1985 versus Climate shift

The impact of LUCC from pristine LUC to 1985 on the discharge was assessed by comparing the simulations using T0 LUC (around the Year 1500) and 1985 LUC. The results are presented on Figure 19. Similar to the previously described scenarios A to E (Table 4), it was observed an increase in discharge for the scenarios I to IV (Table 5).

Simulated discharge considering scenarios I and II, that relates to LUCC between T0 and 1985, presented an increased higher discharge increase if compared to scenarios A and B. The highest increase of average annual median discharge is at the Lower Tietê river outlet (55%) as a consequence of the large LUCC in the upstream subbasins. Note that 1960 already registered enough changes in LUC to impact the discharge within the basin. In these subbasins, the natural vegetation areas that were composed mostly by forests were replaced mainly by grassland and cropland (see Figure 16).

Scenario III assesses the effect of the precipitation change due to the climate shift (between 1961 – 1973 and 1978 – 1990) considering the T0 LUC. Similar relative changes as to scenario C (with LUC 1960) were achieved. Scenario IV resulted on similar discharge changes as for scenario D.

Finally, scenario V assesses the consequence of changes in LUC from T0 to 1985 and in precipitation due to the climate shift, together. Again, the highest changes in discharge were observed at the Lower Tietê that presented an increase of about 85% in the average annual median. At the river mouth of the UPRB (the Lower Paraná site), the discharge increased by more than 50%.

Out of the 10 river outlets analyzed, the scenarios I to IV revealed that the changes in precipitation had a higher impact on the annual discharge than the LUCC in 8 of them. The Lower Tietê and the Upper Paraná sites, changes in precipitation over the Tietê subbasin were lower than in the southern part of the basin which were exceeded 20% (see Figure 6). In the southern part of the basin, despite the important observed LUCC, the changes in precipitation had a greater impact on discharge. This becomes clear when analyzing the changes in discharge at the Lower Paraná, Scenario I and II, related to LUCC, indicate a discharge increase of about 15%, while the climate shift scenarios (III and IV) of about 30%.

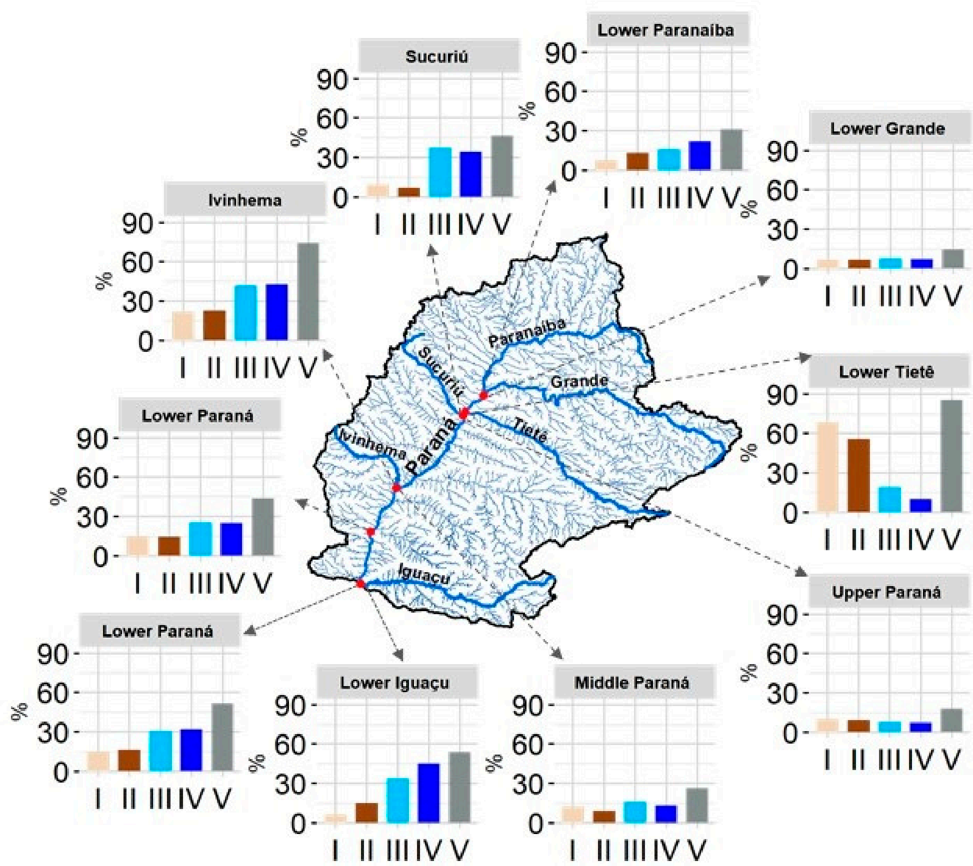

Figure 19. Relative changes (%) in the average annual median discharge at the largest river of the UPRB in scenarios I to V. The scenarios are defined in Table 5.

4 Main conclusions

This thesis aimed to investigate the changes in precipitation and LUCC and their effects on the hydrological processes in the UPRB. To fulfill the major goal, the research was organized into four parts.

The trends of annual and seasonal precipitation, as well as extreme precipitation events over the UPRB using the MK test, were investigated. The significant trends were analyzed at the 95% confidence level using the data from 853 rain gauge stations during the period 1977 – 2016. The main conclusions are presented as follows:

1. The northern and southern regions of the basin presented decreasing and increasing trends in precipitation amounts, respectively.
2. In the southern part of the UPRB, an increase of extreme precipitation events with annual maximum 5-day precipitation and in the number of rainstorms (> 50 mm/day) was observed.
3. The northern part of the basin presented an increase in the number of consecutive dry days (< 1 mm).
4. Most of the areas across the UPRB presented an increasingly long rainy season.

The UPRB was built with the highest possible spatial discretization using the SWAT model for a long-term period between 1984 and 2015. The model was calibrated and validated for the main rivers of the basin. The main contributions of the work can be drawn:

1. Satisfactory SWAT calibration and validation of the monthly discharge from main rivers and LAI values were achieved. Thereby, the proposed project could be used for other studies not addressed in this thesis such as climate change scenarios.
2. The methodology used in this work regarding data preparation, model setup, and strategies for calibration and validation, as well as evaluation, can be used for other large-scale basins, especially in South America.

It was estimated the hydrologic response to LUCC between 1985 and 2015 in the UPRB. The effects of LUCC were addressed for the annual, wet and dry season during the period 1984 – 2015. The main conclusions from the simulated scenarios are presented as follows:

1. Most of the major subbasins presented an increase in the surface runoff and soil moisture amounts in the annual and wet season values, while a decrease was observed in the dry season.

2. A significant decrease in actual evapotranspiration in the annual and wet season values was observed.

3. LUCC induced an increase in discharge in the wet, while a decrease in the dry season.

4. Several rivers had little changes in their discharge due to the compensation of discharge in the wet and dry season.

The effects of LUCC and 1970s climate shift on the changes in the average annual median discharge at the largest rivers of the UPRB were estimated. The numerical simulations were performed using three LUC from a pristine period (around the Year 1500), 1960 and 1985. The scenarios were conducted through the SWAT model during the precipitation period from 1961 to 1990. The following conclusions from the simulated scenarios can be drawn:

1. It was observed that more than half of natural vegetation (forest or cerrado) until the LUC 1985 was suppressed.

2. A significant increase in average median precipitation in most of the areas across the basin after the 1970s climate shift event was observed.

3. Both LUCC and climate shift have a significant impact on the annual discharge at the largest rivers of the UPRB, but with the climate shift being the main driver.

4. The greatest impacts in the annual discharge were observed mainly at rivers located in the southern parts of the basin following the highest increase in precipitation rates observed.

This research is the first to analyze precipitation trends using a large number of rain gauges (853) over the UPRB during a long-term period 1977 – 2016. Furthermore, it is the first to address the integration of both LUCC and climate shift effects on hydrology in the UPRB using a model at a high spatial resolution. The trends analyses revealed that special attention should be paid to the northern and southern regions of the basin, which presented decreasing and increasing trends in precipitation amounts and in extreme precipitation events, respectively. Both regions have an important role in various sectors of the economy and development of Brazil. The LUCC scenarios from 1985 and 2015 indicated that the natural vegetation suppression increased the discharge in the wet season, and decrease in the dry season. In addition, the simulations indicated that both LUCC (from T0, 1960, and 1985) and climate shift have a significant impact on the annual discharge at the largest rivers of the UPRB. However, the main driver is the climate shift, which affected mainly the southern region of the basin.

The provided results describing what happened in hydrology over the past decades under the effects of climate shift and anthropization, investigated here at large-scale basin should be regarded with much attention by the environmental managers worldwide. Hence, future conservation and sustainable use of water resources could be achieved.

4.1 Future work

In spite of the valuable results presented in this thesis, more research is needed within the UPRB. The following future work intended to be developed:

- To extend the evaluation to climate change scenarios.
- To investigate the effect of projection of future LUCC.
- To simulate the effect of the observed agricultural expansion with different types of crops.
- To use the SWAT project performed for the UPRB to investigate concerns related to water quality within the basin.
- To quantify the economic valuation from the anthropogenic impacts on hydrology across the basin.

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